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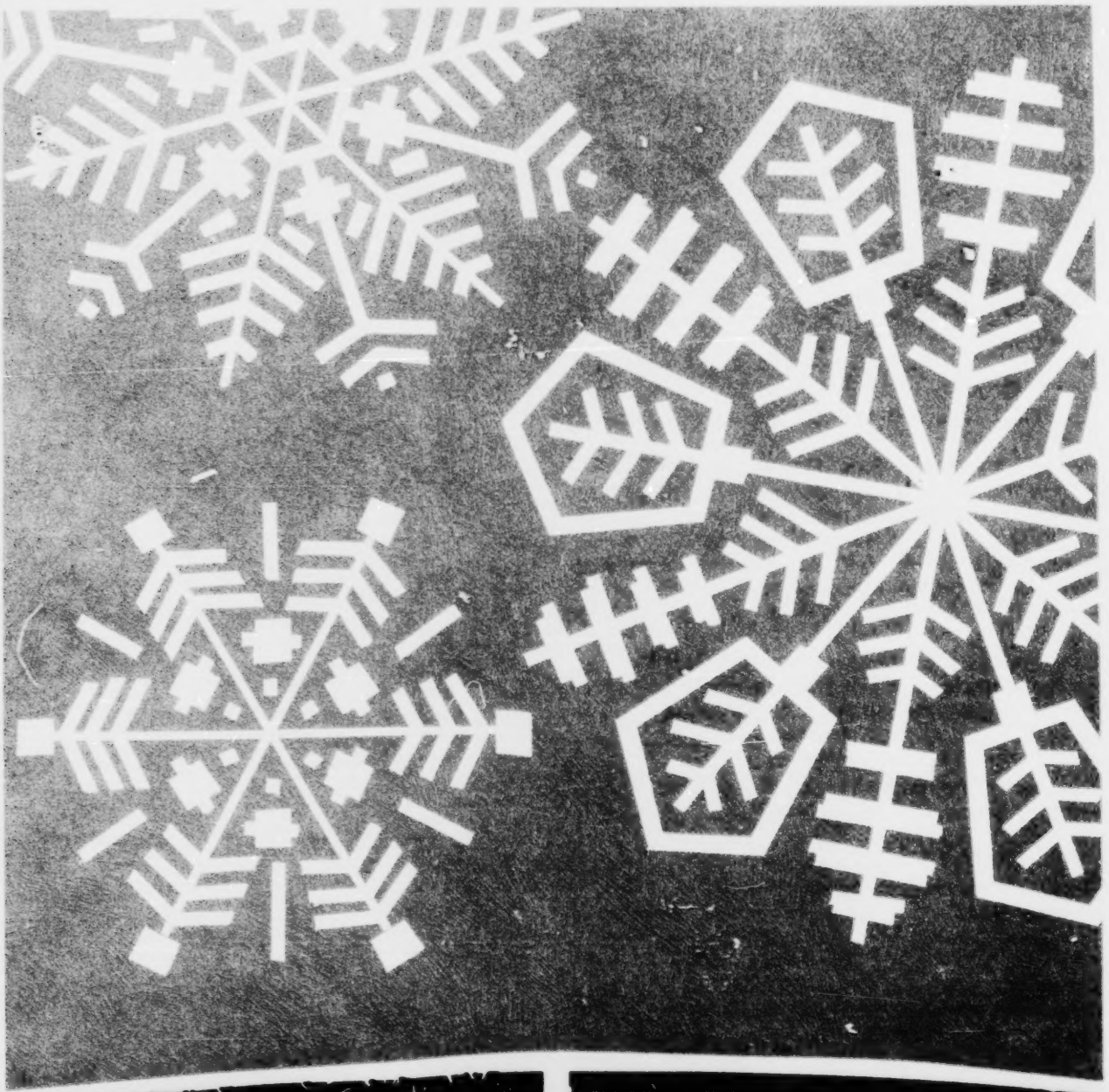
Policy
Planning and
Research Division

Aspects of Prolonged Exposure of Pavements to Sub-Zero Temperatures

Parts 1 and 2



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Aspects of Prolonged Exposure of Pavements to Sub-Zero Temperatures

Part 1
Measurement and Prediction of Frost Penetration in Highways

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Report presented at the Annual Conference of the Roads and Transportation Association of Canada, Ottawa, September 1978.

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Foreword

This report discusses two aspects of highways in Ontario which are created by the exposure of pavements to prolonged sub–zero temperatures. These are the penetration of frost beneath the pavement structure, and the insulation of the pavement in order to avoid adverse frost heave resulting from ice formation.

Frost penetration can cause devastating damage to a pavement in the form of frost boils and uneven frost heave in both the longitudinal and transverse directions which, when excessive, is a hazard to vehicles travelling on the pavement. Designing the pavement structure to avoid or minimize frost damage requires a knowledge of the penetration depth of frost. Part 1 of this report documents a five–year program of measurement of frost penetration, and presents a frost penetration/air freezing relationship, and a freezing index map prepared from temperature records covering 30 years. The report also favourably compares measured frost penetration with predictions made by means of a computerized solution to heat flow relationships.

Hazardous frost heaves have been successfully treated by installing extruded polystyrene foam insulation known as STYROFOAM®. Part 2 documents the results of a five–year program of measurements to determine the ability of various thicknesses of STYROFOAM® to prevent or reduce frost penetration under pavements. These measurements verified the predictive accuracy of a two–dimensional finite element heat flow computer program in two instances, but revealed problems with thicker layers of insulation. Design is facilitated by a set of curves to predict frost penetration under various thicknesses of insulation at locations with different degree–days of freezing temperatures.

W.A. Phang

Abstract – Part 1

Knowledge of the depths of frost penetration in highway roadbeds is essential to determine the safe location of structural foundations, sewers, pipelines, and watermains. To a great extent, current knowledge of frost penetration is the result of sparsely documented experience gained from studies on boreholes and excavations, although a method of prediction exists which relates frost penetration to air freezing index.

Through a five–year program of measuring frost depth by use of frost depth indicators at 62 locations in Ontario, a body of data has been acquired and used to make the frost penetration versus air freezing index relationship more appropriate to Ontario. To further assist the user of this relationship, a freezing index map of the province has been created from published temperature data, observed at 224 locations during the period from 1941–1970. The map was prepared using a method recently developed by the National Research Council of Canada which calculates the air freezing index from mean monthly temperatures.

While the method is simple to use, certain local factors such as soil type and moisture content influence the actual depth of frost penetration. To enable such effects to be evaluated, and to provide the capability of examining the effects of insulation and frost retaining layers, a computerized solution of the heat flow relationships was developed for the Ministry by Carleton University. The program is able to predict the maximum frost penetration and ground temperatures from input information which is, in most cases, readily available. Computer predictions at several sites have been favourably compared with measurements of actual frost penetration/time profiles.

Abstract – Part 2

Since the first successful treatment of a frost heave problem in 1966 using STYROFOAM® HI brand extruded polystyrene foam insulation, Ontario has used substantial quantities of insulation. However, knowledge of the performance of the insulation has been limited to sparsely documented observations of some differently insulated sites. In 1972, a joint experiment was launched by the Ministry of Transportation and Communications and the Dow Chemical Company of Canada Limited to construct, instrument, and observe the performance of pavement insulation at Val Gagne in Ontario.

Three thicknesses of insulation were used in the experiment, and four different taper designs. Winter temperature profiles, frost penetration depths, and frost heave measurements were observed during the winters of 1973 to 1977. The results of these observations were used to verify a two–dimensional finite element heat flow computer program intended for use in the design of insulation for controlling frost penetration. While the program accurately predicts ground temperature for uninsulated situations and thin insulated sections, changes in the program are needed to correct inaccuracies in prediction for thick insulations.

The results were also used in the development of a set of frost penetration prediction curves under various thicknesses of insulation and at locations with different degree–days of freezing temperatures. These curves may be used to select the appropriate insulation thickness for any acceptable depth of frost penetration.

STYROFOAM® insulation recovered from the test site after five years shows virtually no structural changes or changes in thermal properties.

Note: STYROFOAM is a trademark of the Dow Chemical Company of Canada Limited.

® Trademark of the Dow Chemical Company of Canada Limited.

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1/Introduction

Winter temperatures in Ontario often reach –50°C and remain for long periods at temperatures of less than –30°C in many parts of the province. In addition, many areas of Ontario experience more than 150 days of below freezing weather each year. Under these conditions, freezing temperatures penetrate from 1.5 m to 3 m below highways and consequent volume changes due to frost action may cause pavement surfaces to heave upwards in spots as much as 0.3 m. Frost heave threatens the integrity of roadway structures, sewers, pipelines, and watermains. To prevent disruption of the services provided by these facilities and to avoid structural foundation problems due to frost action, these structures and foundations must be located below the frost line. Since cost and difficulty increase rapidly with the depth of excavation needed to locate the structure below the frost line, a knowledge of the greatest depth of frost penetration is essential.

Until fairly recently, estimates of frost depth penetration were based on undefined past records of boreholes and excavations carried out by various works departments, contractors and other companies. Theoretical calculations based on heat transfer equations had been used by Sanger in 1963 [1] to produce frost depth penetration curves for different soil types, as illustrated in Figure 1. This figure shows a wide spread between different soils. For example, at 3000 degree–days (F) there is a spread from 4.7 ft. for clay to 12 ft. for sandy gravel. Now in addition to these records, other methods of estimating frost depth penetration under highways are available.

One such method, established by the U.S. Corps of Engineers in 1947 [2] utilizes a relationship between frost penetration and air freezing index. The method was made applicable to Canada by the publication of a freezing index map of Canada by Wilkins and Dujuy [3] in 1954. Further confirmation of the frost penetration/air freezing index relationship was obtained by a Ministry of Transport study at airports throughout Canada [4].

This relationship takes the form P (metres of frost penetration) equals a constant times the square root of F (the air freezing index in degree–days). The method of determining F is described in Section 7 and is identical to the definition given by the U.S. Corps of Engineers.

A more specific relationship for frost penetration versus air freezing index was developed for Ontario highways. A revised freezing index map of the province was created from 30 years of air temperature records taken at 22 locations.

Another method of determining frost penetration, which is becoming more readily applicable because of advances in computers, is through calculation of heat flows given the soil parameters and air temperature regime.

Both methods are examined in this paper and compared with actual frost penetration measurements. The advantages and disadvantages of both methods are discussed.

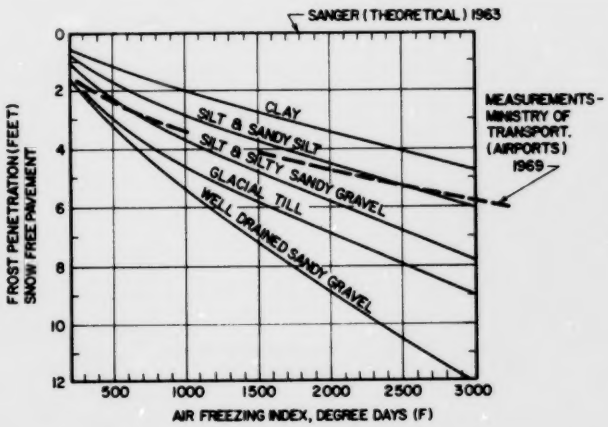


Figure 1/ Frost Penetration Curves Based on Theoretical Calculations

2/Frost Indicators

The frost indicators used to measure frost depth (Figures 2 and 3) are adapted from the Swedish (Gandahl) design and the U.S. CRREL design. The indicators were made and installed by the staff of the Regional Geotechnical Section, MTC, under the direction of the Engineering Research and Development Branch.

The Gandahl type indicator consists of a rigid, transparent, plastic tube with blue indicator solution contained in an annular space created by a soft rubber insert in the tube. The dark blue indicator fluid (0.05% methylene solution) turns white when frozen. The indicator tube is buried in the pavement surrounded by a close–fitting, telescoping casing. The length of tube required is estimated from the freezing index at the location of the installation.

To read the depth of frost penetration, the covering cap is unscrewed, the indicator tube withdrawn, and the depth of the frozen white so-

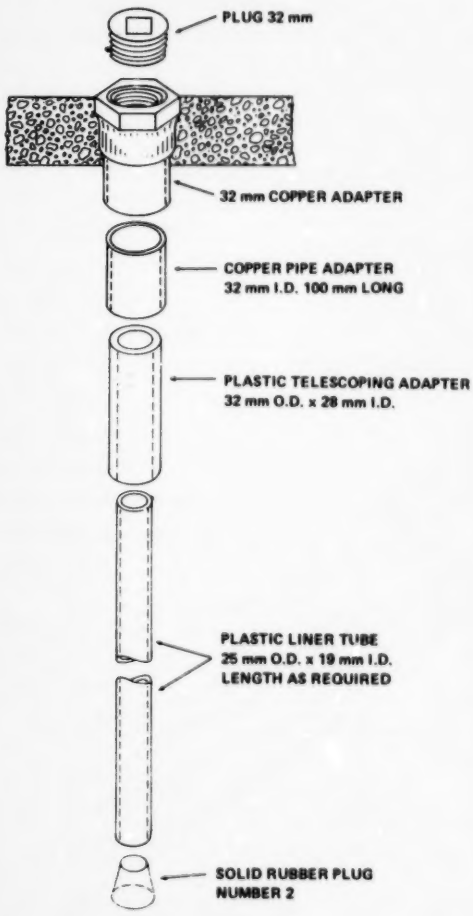


Figure 2/ Gandahl Type Frost Depth Indicator Casing Assembly (MTC Design)

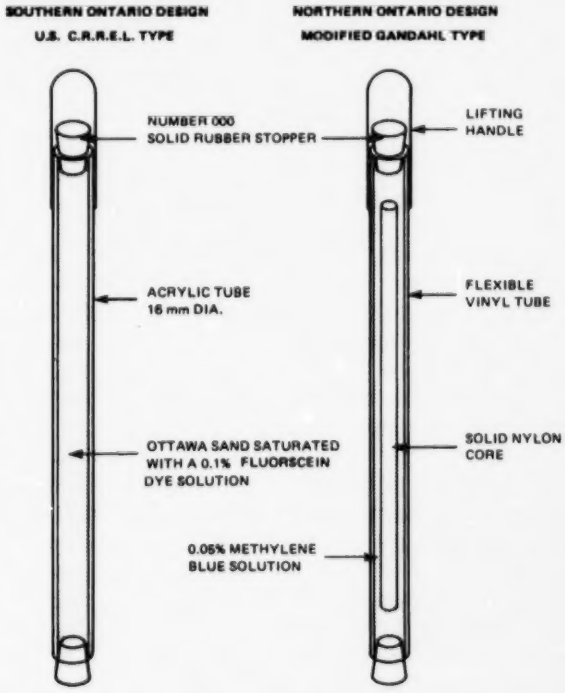


Figure 3/ Gandahl Type Frost Depth Indicator Assemblies (MTC Design)

lution measured. The depth of thaw which occurs is also evident in the spring, when the melted indicator solution at the top regains its blue colour.

In the two northern regions of Ontario, a modified design (Figure 3) is used because the lengths of acrylic tubing needed for the indicator tube are usually too short. The rigid acrylic plastic tube with a soft rubber insert was replaced by a soft transparent vinyl tube with a solid nylon insert. The same methylene blue indicator solution, however, is used.

In 1975, an indicator designed and developed by the U.S. Army Cold Regions Research and Engineering Lab was used in three Ontario regions. This indicator consisted of a rigid acrylic plastic tube filled with a saturated mixture of Ottawa sand and a fluorescein dye solution. The dye, a natural, lime green colour, turns brown upon freezing. This type of indicator more closely parallels natural soil conditions and is now used in the southern regions of the province.

After four years of use, several frost depth indicators of the Gandahl type were replaced due to damage, or were made longer so that deeper frost penetrations could be measured.

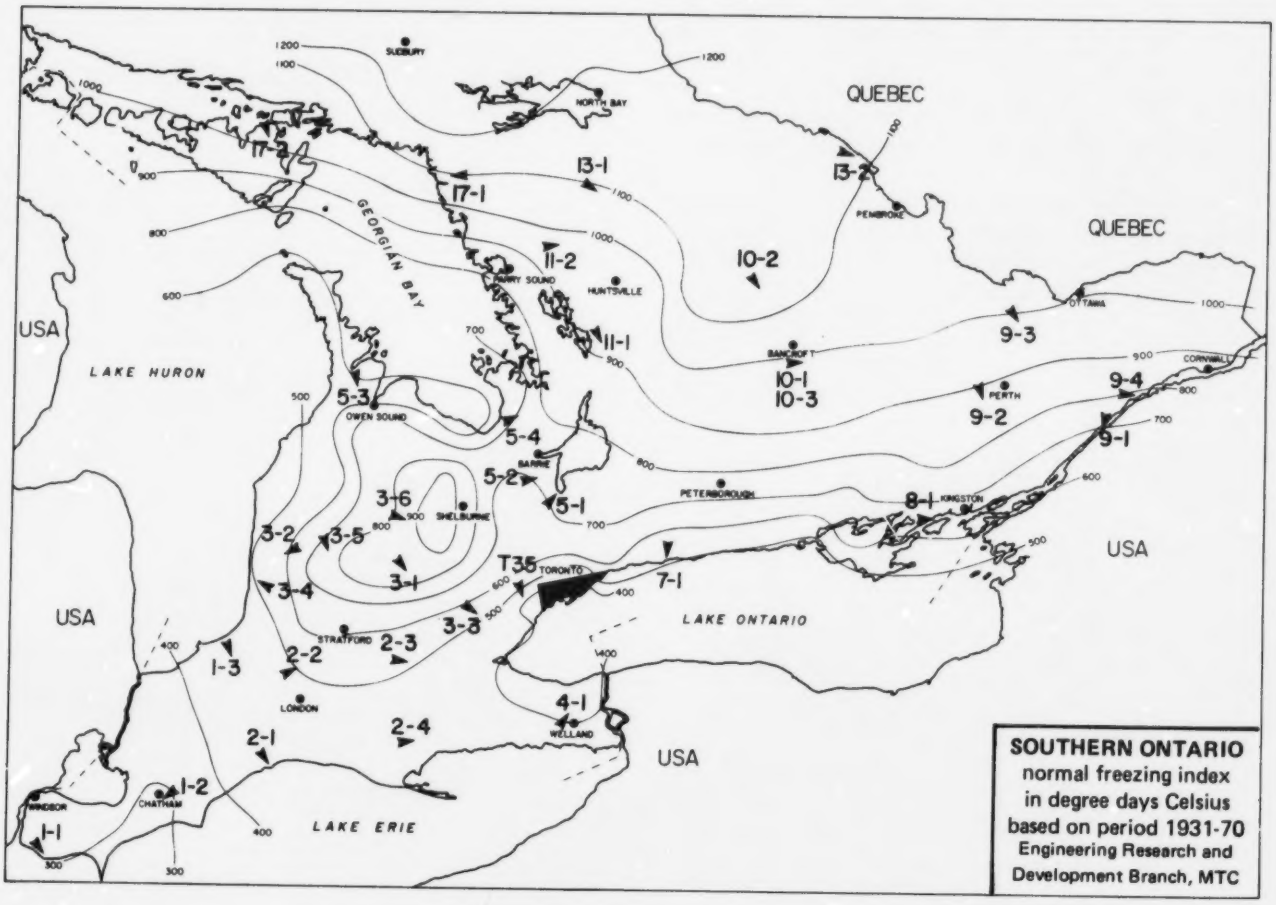
3/Frost Depth Measurement Program

The locations of the frost depth indicators were selected by members of the Regional Geotechnical Section according to subgrade soil types and geographical distribution. During the fall of 1970, 33 frost depth indicators were installed in 15 districts in the 5 regions of the province. During the next two years, an additional 29 frost depth indicators were installed, increasing the distribution to 17 districts in the 5 regions. Indicators were installed near district patrol yards for convenience.

Each indicator is identified by a two–number set: the District number separated by a dash from the number of the indicator (expressed in ascending numerical order beginning at 1) in its particular district. The approximate locations of the indicators are shown in Figures 4 and 5, the freezing index maps of northern and southern Ontario, respectively.

The indicator tubes are maintained by Regional Geotechnical and Section staff, but mea-

Figure 4/ Frost Depth Indicator Locations 1974-1975 Southern Ontario



surements are taken periodically and recorded by members of District Patrol Yards. Examples of the recording forms which show frost penetration depths measured at different dates are given in Figures 6 and 7.

Figure 5/ Frost Depth Indicator Locations 1974-1975 Northern Ontario

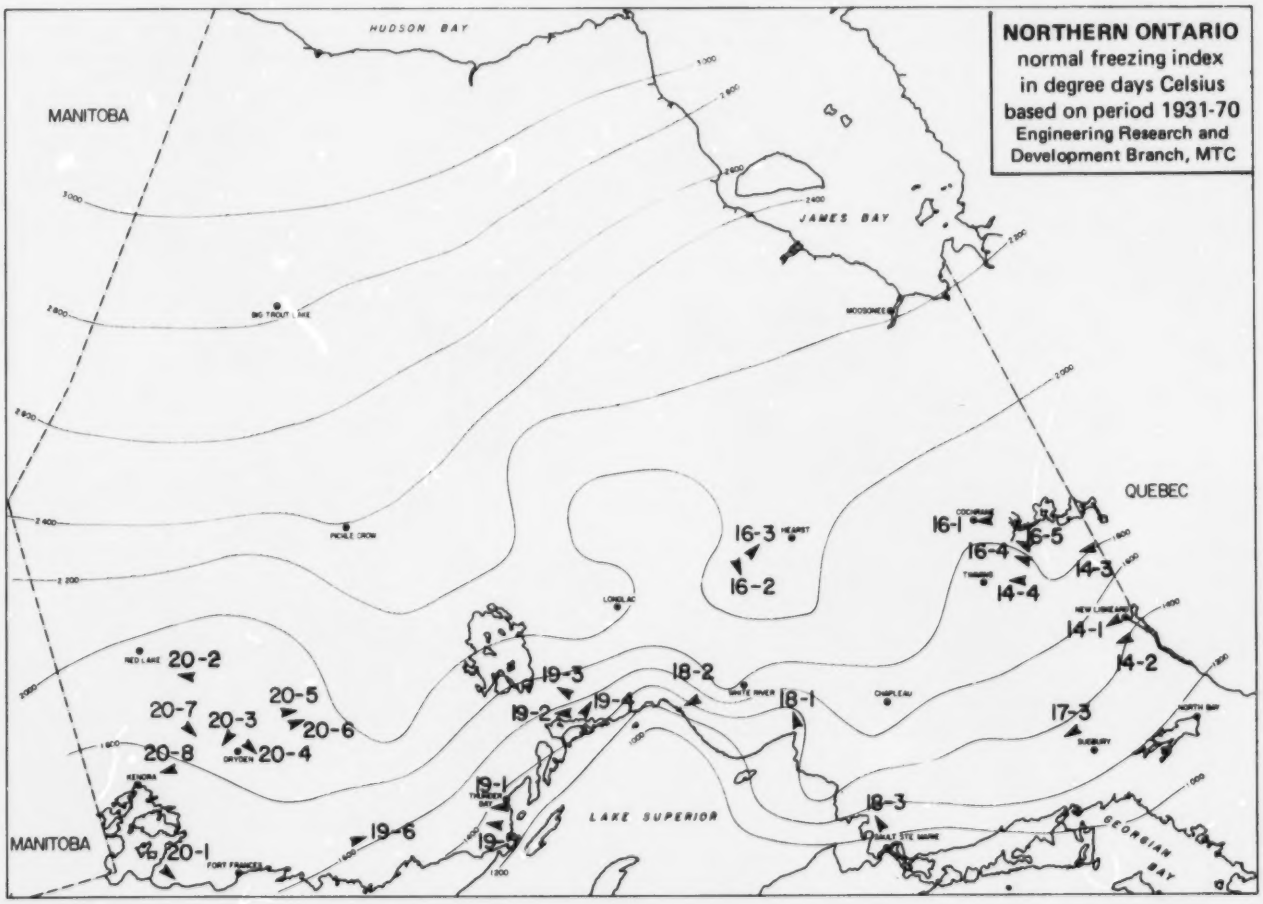
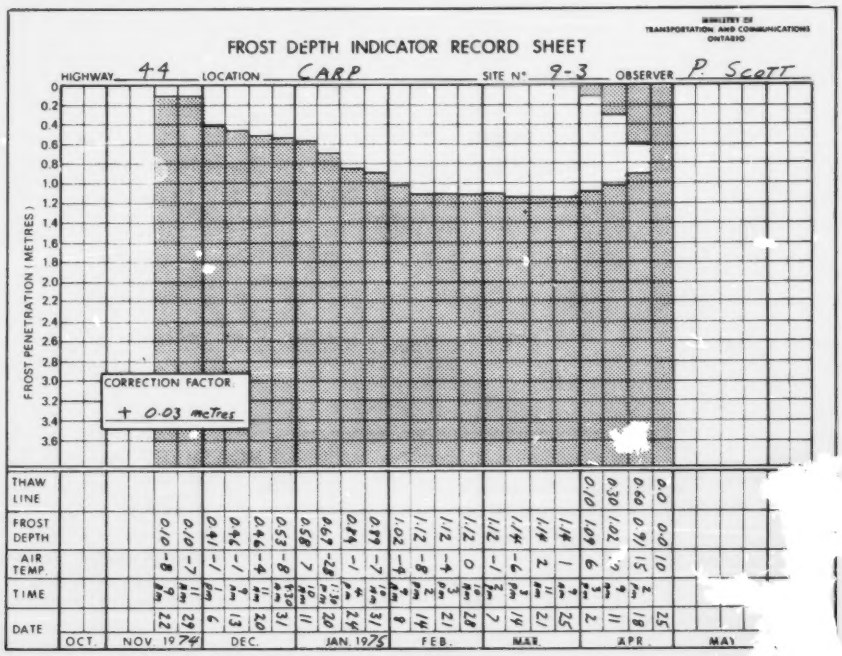


Figure 6/ Example Data Sheet from Southern Region of Ontario



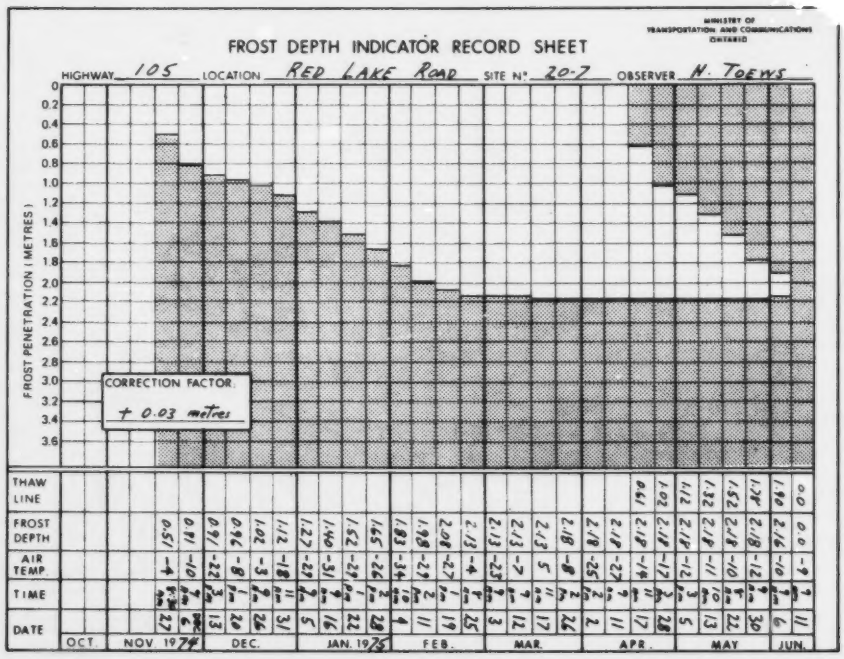


Figure 7/ Example Data Sheet from Northern Region of Ontario

4/Air Freezing Index

Site details for the installations are given in Table 1. The results of the frost penetration measurements taken over five seasons from 1970 to 1975 are summarized in Table 2.

These frost measurements were correlated with the air freezing index calculated from air temperature records at the nearest weather stations. Sites not situated close to a weather station were not used in the correlation. The freezing index is defined as the number of degree–days (above and below 0°C) between the highest point in the autumn and the lowest point in the spring on the cumulative degree–day time curve for one winter season (Figure 8).

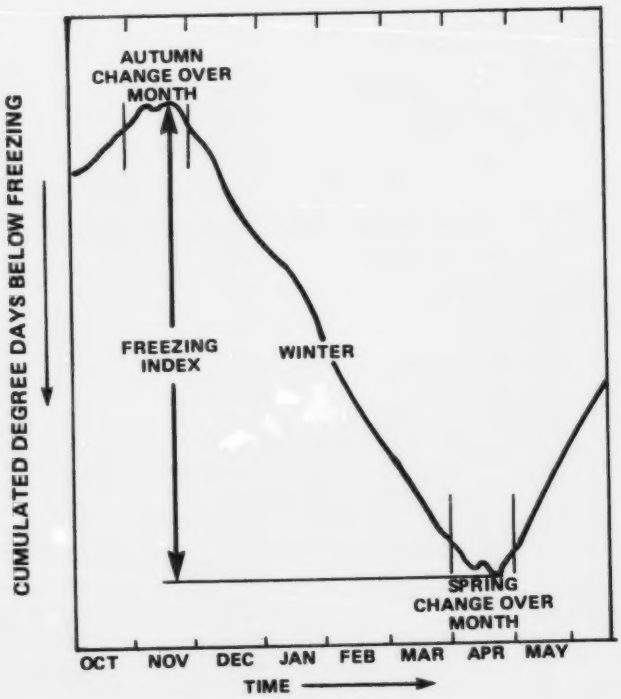


Figure 8/ Calculation of Freezing Index

Table 1/ Frost Depth Indicator Location Details

Region	Dist. No.	No.	Location	Pavement Thickness (mm)	Soils Log Granular Depth (mm)	Subgrade Material
London	1	1-1	Harrow	83	460	Fine Sand
	1	1-2	Chatham	83	610	Fine Sand & Silt
	1	1-3	Port Franks	83	460	Sand
	2	2-1	Wallacetown	83	460	Silty Sand
	2	2-2	Eiginfield	83	460	Clay
	2	2-3	Ayr	83	460	Sand & Fine Gravel
	2	2-4	Langton	83	460	Sand
	3	3-1	Arthur	76	990	Sand
	3	3-2	Wingham	83	610	Clay, Loam
	3	3-3	Guelph	100	460	Sand & Gravel
	3	3-4	Clinton			
	3	3-5	Fordwich			
	3	3-6	Conn			
	5	5-1	20 S. Barrie	76	710	Sand
	5	5-2	Cookstown			
	5	5-3	Clavering	83	460	Sandy Loam
	5	5-4	Elmvale			
Toronto	6	T35	Brampton	140	610	Clay
	4	T6	Brantford	140	230	Gravelly Sand
	4	4-1	Welland	76		Clay
	7	7-1	Bowmanville	230*		Clay
Kingston	8	8-1	Millhaven	102	360	Clay
	9	9-1	Iroquois	76	740	Clay
	9	9-2	Perth	102	660	Clay
	9	9-3	Carp	76		Sand
	9	9-4	Morrisburg	76		
	10	10-1	Bancroft	76	380	Gravelly Silt
	10	10-2	Whitney	76	230	Sand
	10	10-3	Bancroft	76		Sand
North Bay	11	11-1	Bracebridge	76	205	Sand
	11	11-2	Dunchurch	102	410	Sand
	13	13-1	Sunridge	102	180	Sand
	13	13-2	Deep River	102	460	Sand
	14	14-2	New Liskeard	180	690	Clay
	14	14-2	Cobalt	102	660	Sand
	14	14-3	Matheson	102	76	Sand
	14	14-4	Timmins			Clay
	17	17-1	Britt		205	Sand
	17	17-2	Little Current	51	380	Sand
	17	17-3	Cartier	25	1090	Sand
Thunder Bay	16	16-1	Cochrane	102	360	Silty Clay
	16	16-2	Nagagami	152	510	Sand
	16	16-3	Shekak River	140	485	Sand
	16	16-4	Val Gagne	76	915	Clay
	16	16-5	Iroquois Falls	76		Clay
	18	18-1	Wawa	65	725	Sand
	18	18-2	Marathon	76	150	Silty Clay
	18	18-3	Sault Ste. Marie	115	950	Clay
	19	19-1	Thunder Bay	51	510	Clay
	19	19-2	Nipigon	102	1170	Silty Clay
	19	19-3	15 Mi. N. Nipigon	65	850	Sand
	19	19-4	10 Mi. E. Nipigon	140		Heavy Clay
	19	19-5	Thunder Bay	260	760	Clay
	19	19-6	31 Mi. W. Atikokan	130	1090	Light Clay
	20	20-1	Rainy River	40	570	Silty Clay
	20	20-2	Ear Falls	65	420	Sand
	20	20-3	Dryden	115	800	Silty Clay
	20	20-4	Dryden	130	710	Sand
	20	20-5	Sioux Lookout	65	395	Silty Clay
	20	20-6	Sioux Lookout	65	420	Sand
	20	20-7	Red Lake Road	N.D.		
	20	20-8	30 Mi. E. Kenora	130		Sand & Gravel

*Concrete

Table 2/ Ontario Frost Penetration Results 1970-75

No.	Degree Days Celsius (From Map)	Predicted Frost Penetration (m)	1970-71 Degree Days Celsius	1970-71 Maximum Frost Penetration (m)	1971-72 Degree Days Celsius	1971-72 Maximum Frost Penetration (m)	1972-73 Degree Days Celsius	1972-73 Maximum Frost Penetration (m)	1973-74 Degree Days Celsius	1973-74 Maximum Frost Penetration (m)	1974-75 Degree Days Celsius	1974-75 Maximum Frost Penetration (m)
1-1	300	0.62	Indicator		400	0.71	190	0.53	300	0.61		N.D.
1-2	300	0.62	Installed			0.84		0.74		0.79	170	0.56
1-3	450	0.88	Summer			0.89		0.48		N.D.		0.58
2-1	400	0.78	1971			0.81		0.51		0.66		0.43
2-2	500	0.93				1.05	Damaged		520	0.94	415	0.79
2-3	600	1.06				1.32		1.19		1.22		1.02
2-4	450	0.88				0.91		0.76		0.81		0.61
3-1	900	1.36		1.46	830	1.36	640	1.27	750	1.27	705	1.19
3-2	600	1.06				0.94		0.94		0.94		0.74
3-3	600	1.06				1.57		1.24	705	1.45	650	1.22
3-4	550	1.00			Installed			0.91		0.98	Cancelled	
3-5	700	1.16			Fall			1.51		1.56	Cancelled	
3-6	900	1.36			1972		640	1.42	750	1.50	Cancelled	
5-1	700	1.16		1.51		1.36	Cancelled		Cancelled		Cancelled	
5-2	700	1.16				1.04		0.99		1.07		0.91
5-3	600	1.06			580	1.07	420	0.99	530	1.02	400	0.83
5-4	700	1.16			Installed Fall 1972			1.04		1.16		1.07
T35	500	0.93	720	1.32	670	1.12	480	0.99	580	1.02	Cancelled	
T6	450	0.88		1.40		1.27	Cancelled		Cancelled		Cancelled	
4-1	400	0.78							360	0.71	175	0.64
7-1	500	0.93								1.14		1.14
8-1	650	1.12	890	1.24	No Measurements		555	0.94	660	0.94		0.81
9-1	700	1.16		1.45	Indicator Damaged		Cancelled		Cancelled		Cancelled	
9-2	900	1.36	Indicator Damaged			1.29		1.22		1.07		N.D.
9-3	1000	1.45			1110	1.35	870	1.27	930	1.17	770	1.14
9-4	700	1.16			Installed Fall 1972			1.12	Damaged			1.02
10-1	1000	1.45		1.07	1080	1.40	790	1.09	945	1.36		N.D.
10-2	1100	1.53	Indicator Damaged			1.85		1.98		1.90		1.88
					Full Depth of Ind.		New Indicator					
10-3	1000	1.45	New Indicator		1080	1.68	790	1.65	945	1.59		N.D.
11-1	900	1.36		1.50		1.35		1.14	920	1.27		1.24
11-2	1000	1.45	Indicator Damaged			1.54		1.21		1.25		1.27
13-1	1000	1.45	1335	1.51	1390	1.47	1050	1.31	1330	1.38	1120	1.27
13-2	1100	1.53		1.90		1.93		1.74	1090	1.78		1.71
14-1	1400	1.80		2.22	1670	2.18	1360	2.03	1720	2.01	1500	1.79
14-2	1400	1.80		2.39	1670	2.36	1360	2.23	1720	2.34	1500	2.06
14-3	1800	2.10		1.98		2.06		2.01		2.07		1.88
14-4	1750	2.08			Installed Fall 1972			2.06		2.03		2.10
17-1	1050	1.50		1.62		1.55		1.50		1.47		1.42
17-2	1050	1.50		1.45		1.32		1.27		1.42		N.D.
17-3	1400	1.80		1.85	Ind. Paved Over					1.88		1.70
16-1	1850	2.15	2050	2.37	2170	2.48	1800	2.48	2200	2.49		N.D.
16-2	2050	2.27		2.61	2440	2.78	2000	2.62	2390	2.73		N.D.
16-3	2050	2.27			2440	2.56	2000	2.39	2390	2.51		N.D.
16-4	1800	2.10			Installed Fall 1972			2.39		2.49	1660	2.31
16-5	1800	2.10							2100	2.26		N.D.
18-1	1400	1.80		2.06		2.27		2.01		2.25		N.D.
18-2	1200	1.64		2.06	Indicator Damaged		Cancelled		Cancelled		Cancelled	
18-3	1000	1.45		1.38	1110	2.17	780	1.37	Damaged		Cancelled	
19-1	1350	1.78	1550	1.60	1780	1.70	1280	1.50	1580	1.60	1240	1.35
19-2	1500	1.88		2.01		2.49		2.18		2.16	Cancelled	
19-3	1600	1.96		2.26		2.61		2.16		2.44	Cancelled	
19-4	1500	1.88				2.17		1.83		N.D.	Damaged	
19-5	1350	1.77			1780	1.90	1280	1.73	1580	1.80	Damaged	
19-6	1600	1.96				2.39		2.01		2.16	Cancelled	
20-1	1700	2.04		2.08		2.11		1.93		1.98		1.78
			Full Depth of Ind.		Full Depth of Ind.							
20-2	1900	2.18		1.90		1.98		1.88	2140	1.89	1680	1.78
20-3	1850	2.15	1920	2.09	2050	2.03	1610	2.03	2055	2.01	1650	1.90
20-4	1850	2.15	1920	1.96	2050	2.08	1610	1.96	2055	2.06	1650	2.46
20-5	1900	2.18		1.98	Indicator Damaged		Damaged		2210	1.85		N.D.
20-6	1900	2.18		2.64		2.83		2.56	2210	2.63	1755	2.51
20-7	1850	2.15				2.39		2.18		N.D.		2.18
20-8	1750	2.08			Installed 1972			2.03		2.15		N.D.

5/Frost Penetration Versus Air Freezing Index

During the five years when measurements were taken, Ontario experienced the mildest winters in over 100 years. Weather conditions during the remaining years in which measurements were taken ranged from below to near normal temperatures.

Frost penetration depends on climatic factors and soil conditions. However, this study was primarily concerned with the major variable of air freezing index as a basis for estimating maximum frost penetration. Using the data collected from various locations throughout Ontario, the frost penetration "P" in metres for cleared asphalt pavement was plotted against the corresponding air freezing index degree–days below 0°C. The complete set of data gathered during the five–year study was analyzed by a regression analysis program which showed a correlation equation of:

$$P = -0.328 + 0.0578\sqrt{F}$$

where:
P = frost penetration in metres
F = freezing index in degree–days Celsius

This regression equation line is plotted in Figure 9. The negative values at the lower freezing indices indicate that the freezing index must reach a minimum value before freezing in the road structure will occur.

A recently updated report by the Ministry of Transport (MOT) [4], covering the period 1964 through 1971, gives a relationship for uncovered asphalt airport pavements as:

$$P = -0.61 + 0.068\sqrt{F}$$

The MTC curve for 1970–1975 and the MOT curve for 1964–1971 do not differ greatly. Between 300 and 2500 degree–days Celsius, the average difference between the two curves is approximately 0.11 m. This difference would not be significant in pavement design. The MOT curve frost measurements (1973) indicate deeper frost penetrations above 1 000 degree–days than the MTC curve. This is most likely due to deeper granular structures used in airports, than those normally encountered in highways.

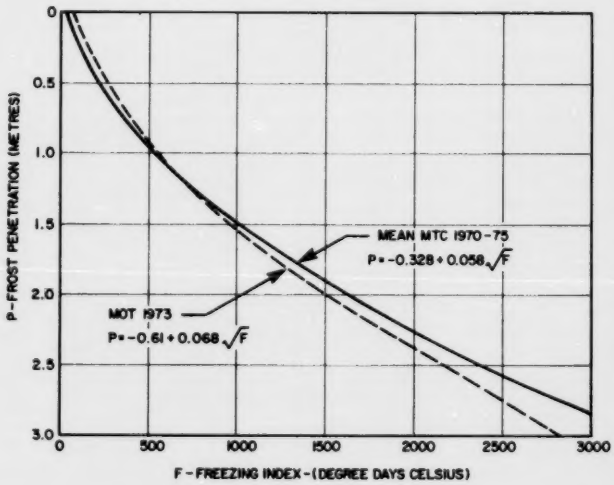


Figure 9/ Frost Penetration in Ontario 1970-1975

6/Effects of Soil Condition and Drainage

Frost penetration is a complex heat flow problem with a great number of other independent variables. Since the frost indicator study used only air temperature as the main variable, some of the results show inconsistencies which may be partly explained by differences in soil conditions.

Soil type and water content can be said to have a combined effect. Gravel and shot rock subgrades with relatively low water contents permit greater frost penetration than clays, which usually have a much greater moisture content. Sand subgrades tend to fall somewhere in between. Dry soils freeze quickly and deeply, and thaw quickly. A wet heavy soil freezes slowly and has less frost penetration.

The effects of soil type and water content can clearly be seen from the results taken at Sioux Lookout. Site 20–5 located in silty clay soil with a high water content, is compared to nearby site 20–6, situated in well-drained sandy soil. The

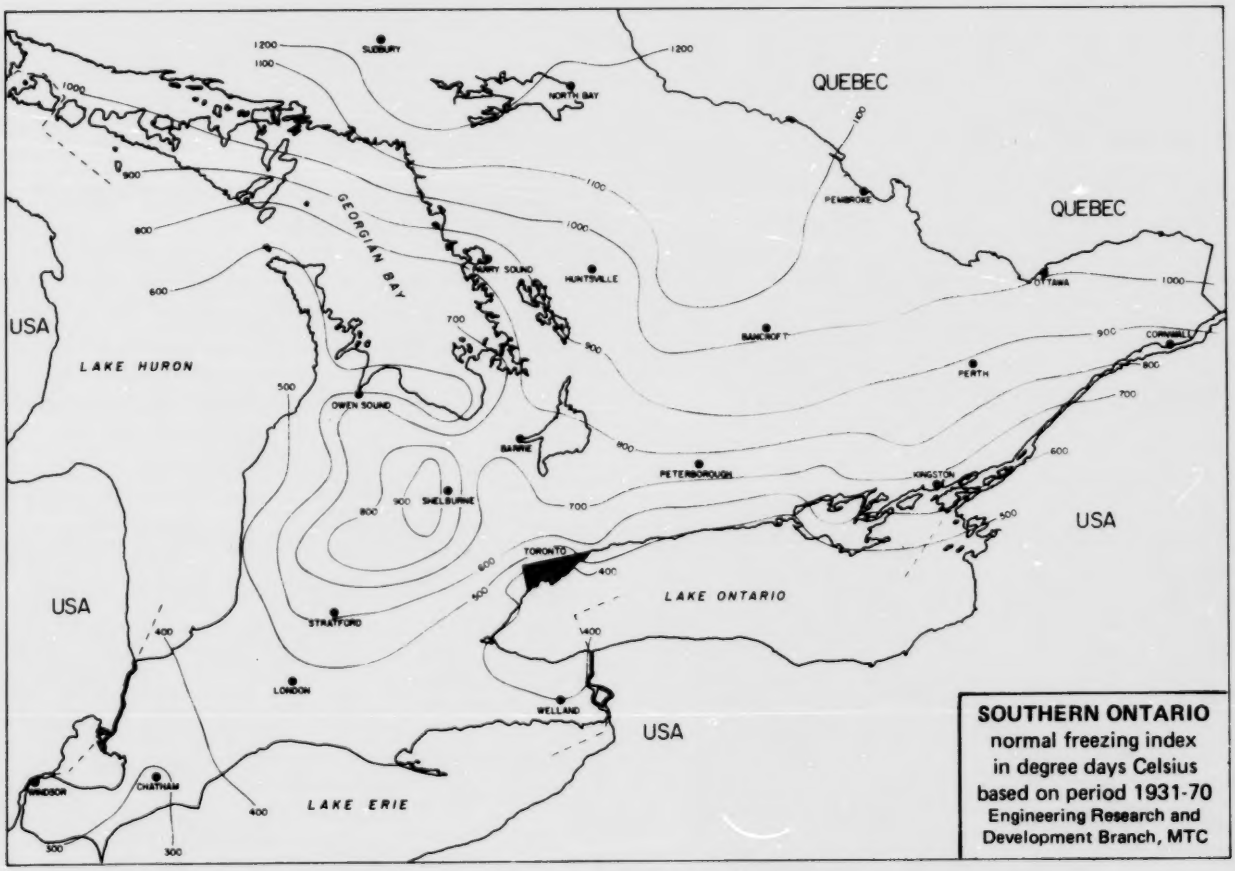


Figure 10/ Freezing Index Map of Southern Ontario

results, which show a difference of over 0.6 m in frost penetration, indicate the significant effect of water on the thermal properties of the soil. The effect of water can be partially explained by the fact that greater amounts of water present increase the volumetric heat capacity to such an extent that a large heat extraction is necessary to lower the temperature.

This same effect is evident at the two Bancroft sites (10–1 and 10–3, Figure 4) and at the Thunder Bay locations (19–1 and 19–5, Figure 5). The wet, heavy soils have less frost penetration than nearby sites located in well–drained, lighter soils.

The graph shown in Figure 9, together with the new freezing index map of Ontario (Figures 10 and 11) can be used to give an approximation of frost penetration. The standard error of estimate was found to be 0.23 m.

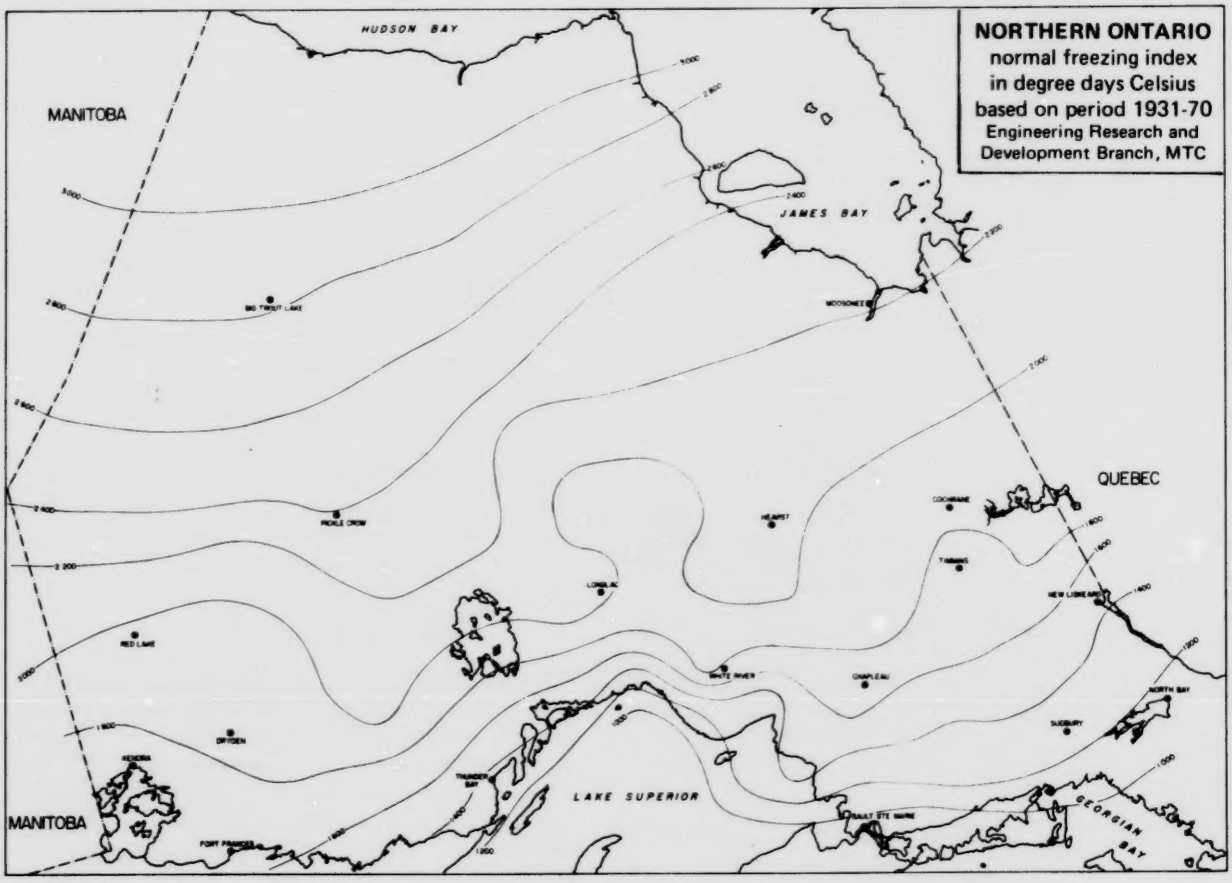


Figure 11/ Freezing Index Map of Northern Ontario

The variation in frost penetration caused by different soils and moisture conditions as measured in this program is not as great as might be expected from theoretical considerations, as is shown by Sanger in Figure 1. A plot of frost penetration predicted by use of the correlation equation (Equation 1) against measured frost penetration shows 80% of the measured points fall within ±0.3 m of the prediction (Figure 12).

As the 62 locations cover a wide range of subgrade types, it appears that for design purposes, one can accept a depth calculated by adding 0.3 m to the frost depth penetration predicted from Equation 1 (Figure 13). Perhaps a somewhat greater allowance needs to be made for very thick granular structures.

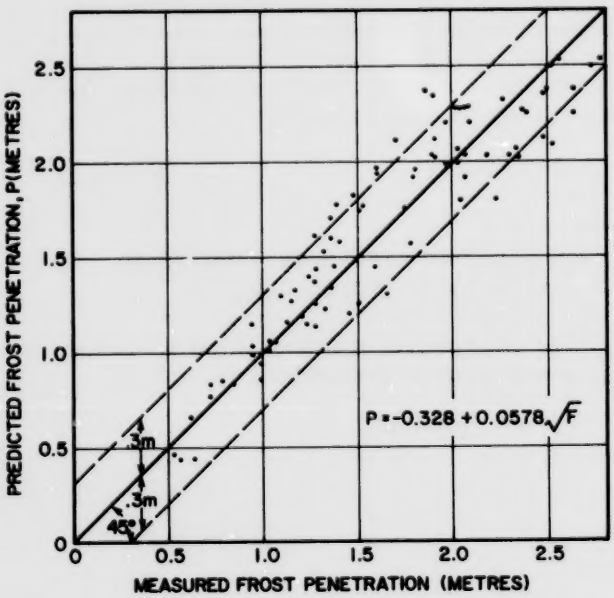


Figure 12/ Observed and Predicted Frost Penetration

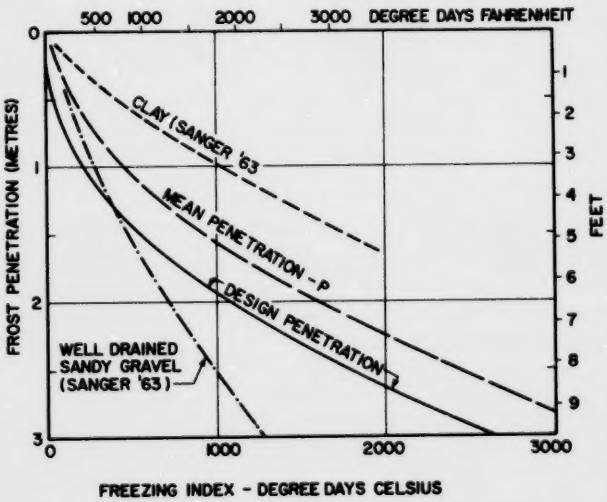


Figure 13/ Design Frost Penetration Curve

7/Freezing Index Map of Ontario

Ontario covers a large, diverse, territory, ranging in the south from the same latitudes as northern California, and northerly to the subarctic shores of Hudson's Bay. The associated temperature regimes and their related depths of frost penetration also vary considerably. Freezing index maps previously used were published by the National Research Council of Canada. However, maps of smaller scale cannot show local variations of freezing index, which can often be significant. Also, since 1975, all temperature data is in degrees Celsius and it was felt that an up–to–date freezing index map using degree–day Celsius was needed.

To construct this map, climatological data for over 200 stations in Ontario available from the Atmospheric Environment Services of Environment Canada [5] were used. The data were used in conjunction with the method described in a recent report by the National Research Council of Canada [6] by which reasonably accurate calculations of air freezing index can be made using monthly mean temperatures. This method, briefly described as follows, was used to calculate the normal freezing index of stations in Ontario which were not included in the report published in 1973 [7].

7.1/Method of Calculation

Since soil freezing depends largely on the extent and duration of depressed air temperatures, it is relatively easy to measure time and temperature by degree–days. One degree–day is defined as the difference of 1°C of the mean daily temperature from the freezing point of water (0°C or 32°F).

These negative differences each day are accumulated over the winter months. Any day that has a mean temperature above freezing (a positive difference) will reduce the accumulated freezing degree–day total. A cumulative plot of degree–days versus time results in a curve similar to Figure 8.

Since the data is accumulated, it is not necessary to begin the plot on any particular date. The freezing index is the number of degree–days between the maximum point in the autumn and the minimum point in the spring.

Previous to 1975, all temperature data was recorded in degrees Fahrenheit and the method for estimating freezing index was based on this data. The following calculation, therefore, uses degrees Fahrenheit.

Any spring or fall month in which the seasonal cumulative degree–days reach a maximum or minimum, as shown in Figure 8, is called a changeover month. The freezing index for all other months is calculated simply by:

$$N\ (32°F - T)$$

where:

N = the number of days in the month
T = the mean daily temperature

For changeover months, Boyd [6] proposed an equation of a hyperbola of the form:

$$y^2 - y\,(t - 32) = k^2$$

If N is the number of days in the month, then the thawing degree–days are given the positive value of y times N and the freezing degree–days by the negative value of y times –N. The value of k is recommended to be 2.5.

The total seasonal freezing index was found by adding together each monthly total, including the changeover months. The error of estimate for normal degree–days based on a 30 year monthly mean temperature would be about 9 degree–days Fahrenheit in the annual totals. However, it should be noted that, because of differences in elevation and topography, nearness to large population centres, proximity to large bodies of water or other sources of heat, variations may be found in annual air temperature of as much as 1°F or 2°F at stations only a few kilometres apart. This could lead to a difference of as much as 100 to 200 degree–days Fahrenheit in the air freezing index over a relatively small geographical area. Thus, no matter how accurate readings are from any one station, a probable error of up to 100 degree–days Fahrenheit is likely for sites within only a few kilometres. Such variations may be significant enough to affect a pavement design, especially in areas with a low freezing index.

7.2/Constructing the Map

The normal freezing index for the climatological stations in Ontario not published was calculated in the above manner from monthly data supplied by the Atmospheric Environment Service of Canada.

The calculated normal freezing index for all 224 stations in Ontario was plotted on two large–scale maps of northern and southern Ontario. The location and freezing index for each station was converted to digital form and the data changed to degree–days Celsius by applying a factor of 0.5555. Several key points on the map were digitized to enable subsequent plots (overlays) to be accurately transferred back to the original maps.

An IBM 375 computer connected to a plotter was used to interpolate the points and draw isopleths at intervals of 100 degree–days Celsius for southern Ontario and at 200 degree–days Celsius for the northern Ontario map. The maps of Ontario and the isopleth plots were then matched and redrawn as shown in Figures 10 and 11. These maps are sufficiently detailed to enable the designer to establish his site location, and to determine an appropriate freezing index.

A test of accuracy of the map was carried out by reading off the freezing index at each frost depth indicator location, and comparing it with the observed freezing indices during 1970–1975.

The comparison, plotted in Figure 14, indicates that the majority of observations fall within ±300 degree–days of the map values. The winter of 1973–1974 was the coldest in the last 10 years, and 1974–1975 was a very mild winter. The map, therefore, reproduces mean conditions very well, and can be used with a fair degree of confidence.

To enable the designer to easily determine the design frost penetration for any given area, design frost penetration maps have been produced. These maps, based on equation 1 plus an additional 0.3 m, were prepared in a similar manner to the degree–day maps. The design frost penetration is plotted directly on two maps of northern and southern Ontario and are given in Appendix A.

Also given in Appendix A is a list of Ontario's major towns and villages together with the corresponding design frost penetration.

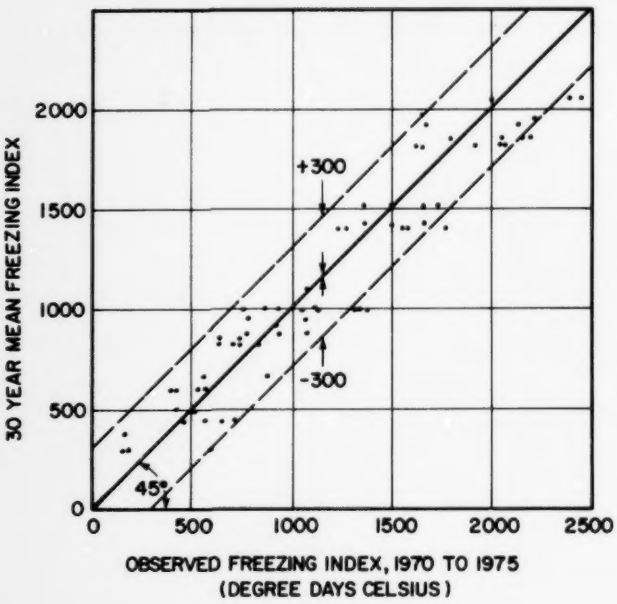


Figure 14/ Observed and Predicted Freezing Index

8/Frost Penetration Prediction by Computer Simulation

The traditional, analytical estimation of frost penetration is frequently based on a number of empirical relationships and formulae developed over the years. Such methods utilize either air or pavement freezing index but take no account of the other key variables, such as soil type and moisture content.

The most common method used is the modified Berggren equation [9] which has been adapted to layered systems such as those found in pavement structures. However, these analytical solutions have weaknesses and restrictions such as the simplifying assumption that all materials have homogeneous soil properties or that all soil moisture freezes at 0°C. An alternative approach for predicting frost penetration is by computer simulation.

A project recently carried out for the Ministry by Carleton University [8] has resulted in a computer program to predict the depth and time pattern of frost penetration beneath pavement structures.

The computer simulation program involves the creation of a numerical, finite difference, heat transfer model of the soil, and the undertaking of a stepwise digital computation in which actual weather regime data is used. Computer simulation not only provides detailed predictions of frost depth and ground temperature conditions, but is able to predict complex and important future events.

8.1/Computer Model

The model as described by Smith [8] is based on the strategy developed by Outcalt (1972, 1975) [10]. The computer program simulates the ground temperature and surface energy regimes for paved surfaces using inputs of synoptic weather data. A simplified flowchart is shown in Figure 15. The main structural elements of the program are as follows:

(a) Inputs of weather data (solar radiation, cloud cover, air temperature, wind speed and atmospheric pressure), together with certain highway characteristics (albedo, aerodynamic roughness) are used to solve the surface energy balance. In general, this is written as:

$$RN = H + S (+ LE)$$

where:

RN = the net radiation balance of incoming and outgoing radiation

H = convection

S = the heat conduction into or out of the ground

LE = the evaporation (assumed to be zero for a highway surface).

(b) The purpose of solving this energy balance equation is to derive the prevailing surface temperature, which is not routinely available anywhere. To do this, the components of the energy balance equation are each expressed as functions of surface (highway) temperature and iterative solution of this equation leads to the equilibrium surface temperature.

(c) The equilibrium surface temperature is then used as the boundary condition, together with the ground thermal properties, to predict the ground temperature pattern via the heat conduction equation. An implicit finite difference solution is used

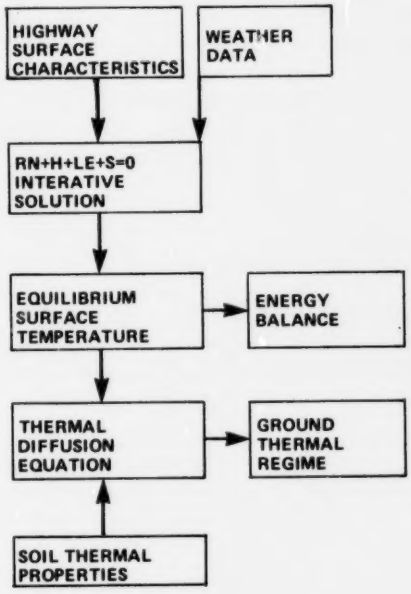


Figure 15/ Simplified Program Flow Chart

(Carnahan, Luther and Wilkes, [11]) which accommodates complex stratigraphy (including frozen and unfrozen states) and freeze/thaw energetics. No account is taken of moisture migration during freezing.

The solution is one–dimensional and thus ignores the finite width of the highway. However, since the depth of frost penetration is considerably less than highway width (approximately 1:10), this is not a serious limitation. Predictions may be viewed as being at the highway centreline.

The program is organized to produce output on a daily basis, using either input of actual daily weather data or daily data interpolated from the input of monthly data. The latter is adequate for the general prediction of frost penetration but, if accurate prediction of the timing of freezing and thawing is required, then it is necessary to use actual daily data. Ground thermal properties may be input directly (where available) or calculated in a subroutine on the basis of physical information supplied by the user. This option is specified separately for each soil layer, (up to a maximum of nine layers). The initial ground temperature profile may actually be specified where data are available or simply preset to arbitrary values, although the former is preferred. The bottom grid is necessarily kept at a fixed temperature in the finite difference calculations. A depth of 6 m is generally suitable for this.

8.2/Input Information

The program uses information which in most cases is widely available. Soil thermal properties are either input directly or may be calculated by a subroutine. If limited soils information is available, "typical" values may be used.

An initial soil temperature profile must be provided. The data may be direct results from thermocouples or thermistors or, if no information on soil temperature is available, an arbitrary temperature may be set based on the mean annual air temperature at the nearest meteorological station.

Climatological data comprises a large part of the input needed for the program. Records published by the Atmospheric Environment Services provide all of the information for simulations. The type of weather data required is solar radiation, cloud cover, cloud type, air temperature, wind velocity and atmospheric pressure. In most cases, it will be necessary to use more than one station to assemble all the data required. Detailed input information for use in the computer program is given in Appendix B.

8.3/Computer Prediction versus Measured Frost Depth Penetration

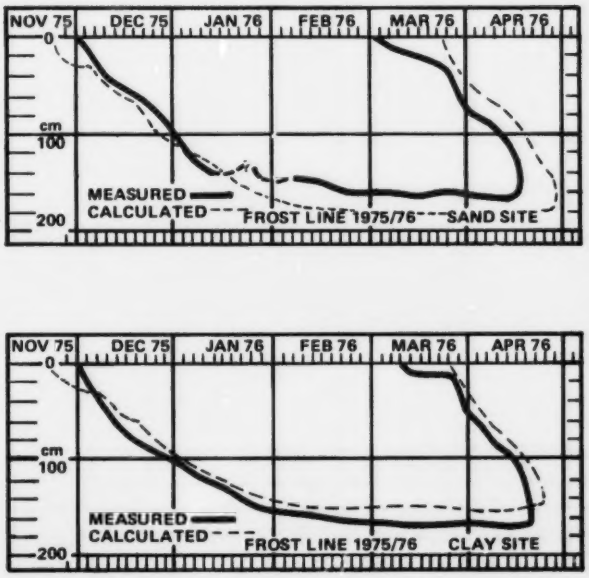
Model predictive capabilities were tested on two specifically instrumented sites in the Ottawa area. The sites were instrumented for the measurement of ground water and temperature in a previous study [12]. Soil samples were available from the sites, one of which was predominantly a clay subgrade and the other mainly sand. Weekly measurements of temperature and ground water provided the data on which the program is based. The observed and simulated frost lines (Smith 1976) [8] are shown in Figure 16 for one of the winters during which measurements were taken.

Although the prediction model is not perfect, the pattern of frost penetration and soil isotherms is realistically produced at both sites. The worst error encountered in predicting the maximum frost penetration was about 10% (15 cm). According to Smith, this disagreement may be due, in part, to the fact that predictions were based on mean daily temperatures, whereas the measurements were all taken in the afternoon when the surface layer would be warmer. Even though the prediction model used very accurate soils information, part of the error may also be due to assigning the soil moisture conditions at the two test sites.

Part of the testing for the model included comparing the results from the frost indicator study with the computer prediction. Four sites were selected from the Ontario network [13] and the necessary weather data were obtained from local weather stations. As only minimal soils information was available, average values were derived from the literature and used in the program.

The observed and simulated frost lines for the four sites are shown in Figures 17 and 18. Agreement is reasonable with only 1% error in the predicted frost depth for Carp, 13% for Millhaven, 15% for Guelph, and 24% for New Liskeard. Although the available soils information is limited, the prediction model correlates reasonably well with the frost depth indicators. It is highly desirable to input accurate soils data, nonetheless, the predictive capabilities of the model are still good even if this knowledge is not available to the designer.

Figure 16/ Observed and Simulated Frost Lines Ottawa Sites, 1975-76



8.4/Insulating Layers

The potential usefulness of a simulation approach is best illustrated by analysis of the efficiency of different insulation materials in reducing frost penetration. The research engineer has an experimental tool available to fully study the effects of an insulating material in a pavement structure before a fullscale field trail is built. Through this method, effects such as layer thickness, placement in the structure, and efficiency under varying climatic conditions may be studied so that engineers can formulate the best design strategies based on the results.

Figure 19 illustrates a design produced for the Raith Swamp on Highway 17. The effect of an 8 cm layer of extruded polystyrene insulation introduced into the pavement structure is clearly visible as the frost penetration is reduced from 1.84 m without insulation to 0.98 m with the insulated layer.

If the computer simulation gives favourable results, a research site may be designed and built with confidence that the insulating material will perform as expected. This process would greatly reduce the number of field trials normally needed to determine the best and most economical use of a new insulating material.

The experiment at the Raith Swamp was constructed in 1977. Actual measurements now reveal that the design computer simulation was fairly accurate. However, when the computer simulation was rerun using actual weather and soils data, the results did not agree with those found with any insulating layer. Disagreement was more marked with the thicker insulating layers.

The simulation did accurately predict penetration in the uninsulated control section. Further work is needed to establish suitable constants for insulating materials for use in this computer simulation program.

The simulation program did agree with measurements in the Noelville experiment with bark as a frost retarding layer, as is shown in Figure 20.

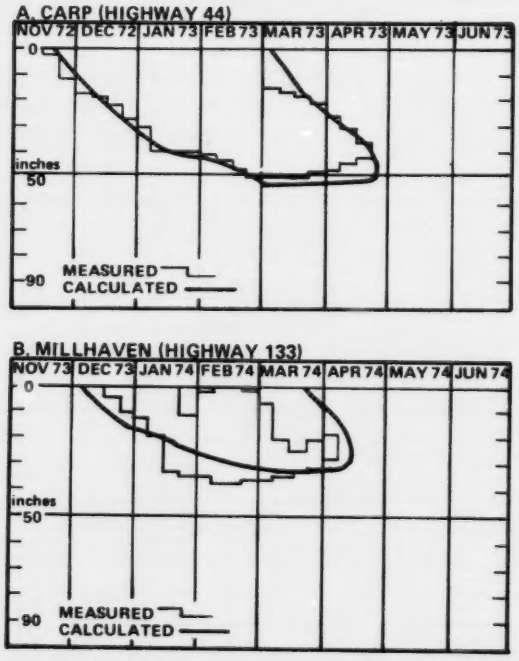


Figure 17/ Observed and Predicted Frost Lines, Carp (a) and Millhaven (b)

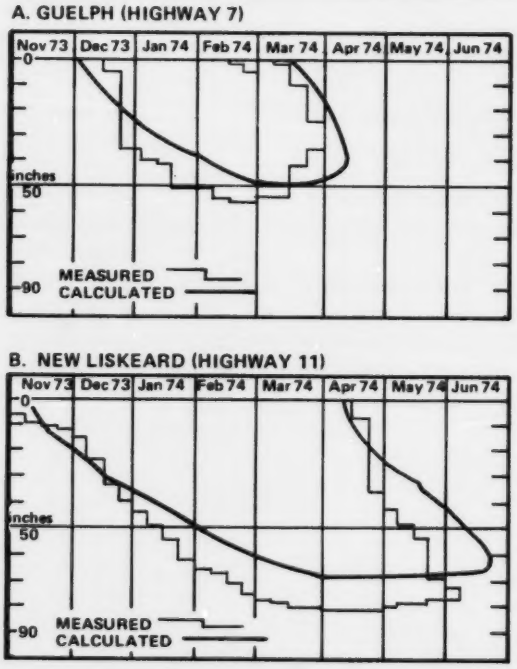


Figure 18/ Observed and Predicted Frost Lines, Guelph (a) and New Liskeard (b)

8.5/Discussion

Because soil conditions are such an important factor in determining the frost penetration in pavement structures, estimates based on calculations rather than the relationships shown in Figure 9 are more accurate. However, the graph in Figure 9 is useful where knowledge of the site air freezing index is required and these indices can be easily obtained from the maps for any location in Ontario.

In trying to predict frost penetration for an area in which construction of a highway is projected, it must be remembered that the depth of frost penetration at any particular location will vary from year to year in relation to the extent and duration of the freezing temperatures experienced. In addition, the soil properties and moisture content will also vary throughout any stretch of highway and thus the depth of frost penetration will also vary. The advantage of computer simulation is that it is able to predict complex future events without actually having to experience them in a field situation.

The program makes possible more accurate time temperature profiles for use in evaluation of the optimum designs for new pavement structures using experimental materials such as tree bark or sulphur foam. The program could also be used to design for the worst possible situation.

The simulation program requires considerably more data and time to be able to predict frost penetration, however, for specific project applications the program can be a major tool for the pavement design engineer.

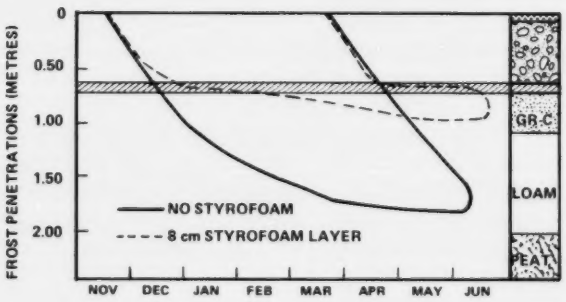


Figure 19/ Computer Simulation of STYROFOAM™ Layer Effect in a Pavement Structure

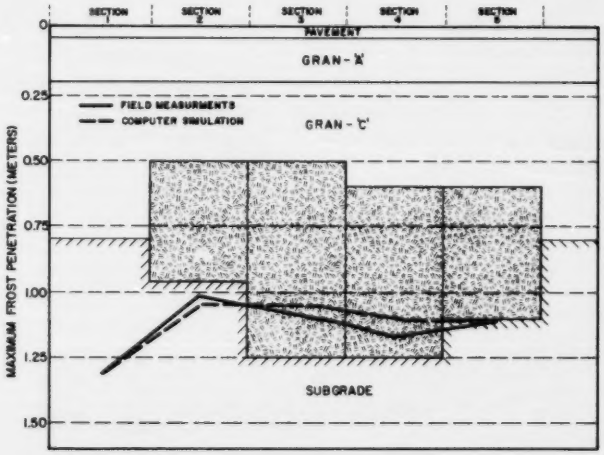


Figure 20/ Observed and Simulated Frost Lines in Experimental Bark Test Sections

9/Spring Thaw

Accurate knowledge of the pavement structure condition during the spring thaw would aid Ministry and municipal maintenance engineers in deciding when to erect signs for the half load legislation.

9.1/Measurements

Ontario's network of frost depth indicators has been used to determine when half load restrictions should apply during spring thaw. The indicators are very accurate when surrounding soil temperatures are below the freezing point of 0°C. As the indicators contain only a very small column of liquid, however, they tend to thaw much more quickly than the mass of material around them. As a result, the indicator shows a thawed condition while the pavement structure may still be solidly frozen. The gauges do, however, give a good indication of when the structure is in a thawing condition and may, depending on the weather, rapidly deteriorate to a much weakened state.

9.2/Computer Simulation of the Spring Thaw

Even though the computer simulation prediction for total frost penetration is reasonably accurate, the same does not apply for the spring thaw prediction. The timing for the thaw below 0.3 m as well as the date of completion can be predicted fairly accurately. The condition of the top 0.2 m to 0.3 m, however, cannot be predicted with certainty as the fluctuating freeze/thaw conditions will depend on the day–to–day weather. If the pattern of thaw is required with some accuracy, it is recommended that the monthly weather data normally used be replaced with daily data after March 15.

10/Conclusions

This report summarizes the results of five years of observations of frost penetration in pavement structures taken across Ontario. The following conclusions have been made:

(a) The modified Swedish–type frost depth indicator is an inexpensive and reliable instrument for measuring frost penetration. The instruments are not accurate in measuring the spring thaw but only indicate when the pavement structure is in a thawing condition.

(b) The relationship between air freezing index and frost penetration was found to be:

$$P = -0.328 + 0.0578\sqrt{F}$$

where:

P = frost penetration in metres

F = freezing index in degree–days Celsius

(c) Frost penetration at two nearby points may vary significantly depending on the soil and moisture conditions present at the site. However, for design purposes an additional 0.3 m would cover this variation (80% confidence level).

(d) An up–to–date metric freezing index map of Ontario is presented that was based on data from 224 climatological stations in Ontario. The mean freezing index from the map is within ±300 degree–days of actual.

(e) A computer program has been developed that is capable of predicting the depth and time pattern of frost penetration beneath pavement structures. The program will enable research and design engineers to fully evaluate problems such as frost heave treatments or new insulating materials which are now being experimented with in highway construction.

(f) The computer simulation program should be used for specific project applications. The relationship based on air freezing index can be used where only a reasonable estimate of frost penetration is needed.

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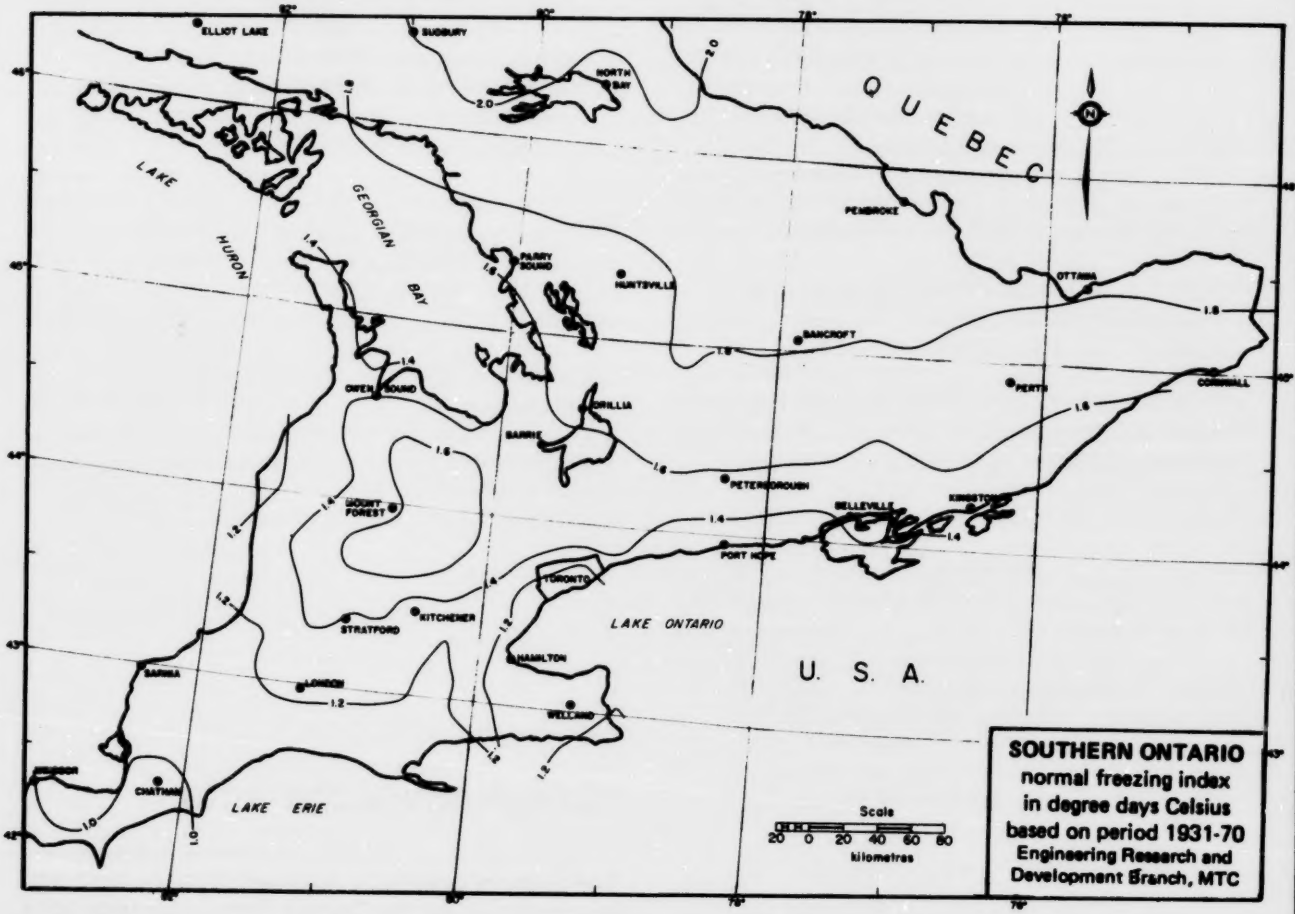
12/Acknowledgments

The authors gratefully acknowledge the help and co–operation of the District Patrolmen who took the weekly gauge readings.

13. Appendix A – Proposed Frost Design Depths

Southern Ontario - Proposed Design Depths for Frost Penetration Beneath Paved Highways (in metres)

Actinolite	1.6
Alexandria	1.8
Algonquin Park Stn.	1.9
Alliston	1.5
Apsley	1.7
Arnprior	1.8
Arthur	1.7
Bala	1.6
Bancroft	1.8
Bannockburn	1.7
Barkway	1.7
Barrie	1.5
Barry's Bay	1.9
Beaverton	1.6
Belleville	1.4
Bobcaygeon	1.7



Bondhead	1.5
Bracebridge	1.7
Bradford	1.5
Brantford	1.2
Britt	1.9
Brockville	1.5
Burk's Falls	1.8
Calabogie	1.8
Caledonia	1.2
Campbellford	1.5
Carleton Place	1.8
Casselman	1.8
Chatham	1.0
Cloyne	1.7
Colborne	1.4
Crosby	
Deep River	1.9
Denbigh	1.8
Dorset	1.8
Dunchurch	1.8
Dunnville	1.2
Durham	1.6
Eganville	1.9
Elmira	1.5
Estaire	2.0
Exeter	1.3
Forest	1.1
Fort Erie	1.2
Gananoque	1.4
Georgetown	1.4
Glencoe	1.1
Goderich	1.2
Gravenhurst	1.7
Grimsby	1.0
Haliburton	1.8
Hamilton	1.2
Havelock	1.6
Hawkesbury	1.8
Huntsville	1.8
Kemptville	1.7
Kingston	1.5
Kincardine	1.2

Kiosk	2.0
Kitchener	1.4
Lake St. Peter	1.9
Leamington	1.0
Lindsay	1.6
Listowel	1.6
Little Current	1.7
London	1.2
Long Point	1.1
Lucan	1.3
Lucknow	1.2
Manotick	1.7
Markdale	1.6
Mattawa	2.0
Morrisburg	1.6
Mount Forest	1.6
Oakville	1.2
Oil City	1.1
Orangeville	1.6
Orillia	1.6
Oshawa	1.3
Ottawa	1.8
Owen Sound	1.4
Napanee	1.5
Niagara Falls	1.1
Noelville	2.0
Norland	1.7
Palmerston	1.6
Parry Sound	1.7
Pembroke	1.8
Penetanguishene	1.5
Perth	1.7
Peterborough	1.6
Picton	1.4
Poland	1.8
Pontypool	1.4
Port Carling	1.7
Port Hope	1.3
Powassen	1.9
Renfrew	1.8
Richmond Hill	1.4
Ridgetown	1.4

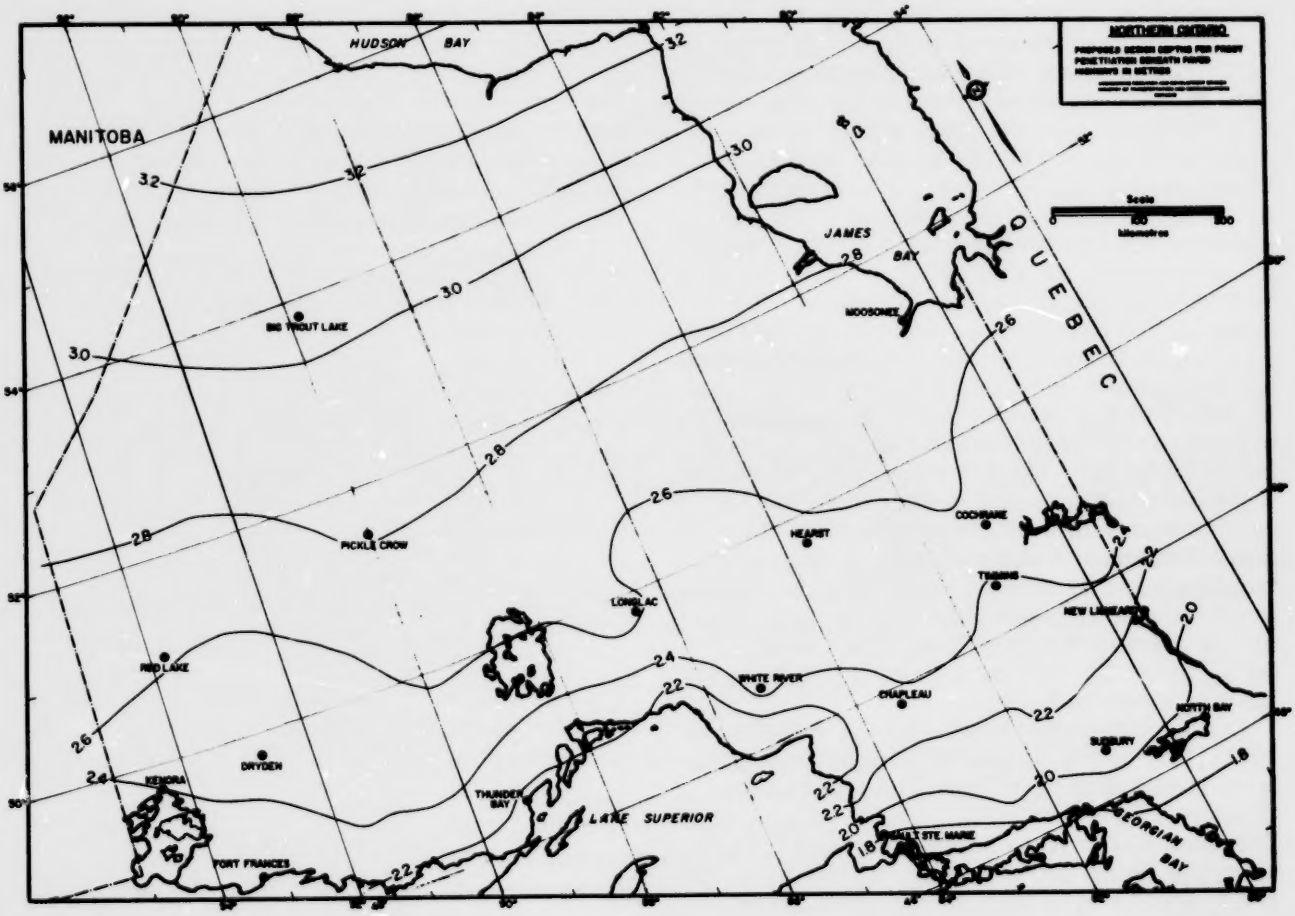
Rockland	1.8
St. Thomas	1.2
Sarnia	1.1
Seaforth	1.4
Shelburne	1.7
Simcoe	1.2
Smith Falls	1.7
Southampton	1.3
South River	1.9
Stayner	1.5
Stratford	1.4
Strathroy	1.2
Sturgeon Falls	2.0
Sutton	1.5
Thornbury	1.6
Tilbury	1.0
Tillsonburg	1.2
Tobermory	1.4
Toronto	1.2
Trenton	1.4
Uxbridge	1.5
Walkerton	1.4
Wallaceburg	1.0
Welland	1.1
West Lorne	1.1
Whitney	2.0
Wiarton	1.4
Winchester	1.7
Windsor	1.0
Wingham	1.4
Woodstock	1.3

Northern Ontario - Proposed Design Depths for Frost Penetration Beneath Paved Highways (in metres)

Armstrong	2.7
Atikokan	2.4
Attawapiskat	2.9
Barbers Bay	2.4
Big Trout Lake	3.1
Cartier	2.1
Chapleau	2.4
Cochrane	2.5
Dryden	2.5
Ear Falls	2.5
Englehart	2.3
English River	2.5
Foleyet	2.4
Fort Frances	2.3
Fort Hope	2.8
Geraldton	2.6
Gogama	2.3
Hearst	2.6
Hornepayne	2.5
Hurkett	2.3
Ignace	2.5
Iroquois Falls	2.4
Kapuskasing	2.5
Kashabowie	2.4
Kenora	2.4
Kirkland Lake	2.4
Lansdowne House	2.9
Little Current	1.7
Longlac	2.6
Loon	2.2
Manitouwadge	2.4
Marathon	2.1
Mine Centre	2.3
Montreal River	2.2
Moosonee	2.7
Nestor Falls	2.4
New Liskeard	2.1
Nipigon	2.3

North Bay	2.0
Orient Bay	2.4
Rainy River	2.3
Raith	2.4
Pagawa River	2.5
Pickle Lake	2.8
Red Lake	2.6
Sault Ste. Marie	1.8
Savant Lake	2.6
Schreiber	2.3
Sioux Lookout	2.5

Smooth Rock Falls	2.6
Spanish	1.8
Sudbury	2.1
Temagami	2.1
Terrace Bay	2.2
Thessalon	1.7
Thunder Bay	2.2
Timmins	2.4
Upsula	2.4
Wawa	2.1
White River	2.4



14. Appendix B – Computer-Predicted Frost Penetration (Carleton University)

Computer Program Input Information: Data requirements for the program use information which is in most cases widely available.

Soil Information: Soil thermal properties can be either input directly (i.e., frozen and unfrozen thermal conductivity, frozen and unfrozen volumetric heat capacity and moisture content) or calculated by a subroutine.

Inputs for the subroutine are:

1. Dry bulk density (g/cm^3)
2. The average winter value of moisture content by mass (g/g)
3. The percent of soil grains larger than 50 microns (#200 seive) measured by mass.

NOTE: See data input forms.

Initial Temperature Profile: An initial soil temperature profile on the date the simulation is started must be provided. The data may be direct results from thermocouples or thermistors or if no information on soil temperatures is available an arbitrary initial temperature may be set at 3.0°C higher than the mean annual air temperature at the nearest meteorological station.

Climatological Data: When the simulation is to be run for a particular site, necessary climatological data have to be provided from the nearest climate station. As all stations do not measure all the variables, it will be necessary in most cases to use two or more stations to assemble all the data needed. All the information needed for simulations using monthly mean data may be found in the Monthly Records published by the Atmospheric Environment Service. For simulation using daily climate data, the information will have to be collected directly from the Applications Branch or from the station itself.

Solar Radiation: Solar radiation is measured in langleys/day and may be input on a daily basis or as a monthly mean value. Since solar radiation is measured in only 5 locations across Ontario, it may be necessary to calculate it on the basis of sunshine hours.

The basic equation used is taken from (Chang, 1971) [14] and the constants calculated using solar radiation data from Ottawa and Moosonee:

$Q = QA\,(0.24 + 0.64 \cdot n/N)$.

The user will have to supply the total monthly sunshine hours (n) and select values from QA and N according to latitude and month from the tables in the Appendix.

Cloud Cover: Cloud cover data as published by the Environment Services is measured on a scale ranging from 0–100, 0 being cloudless sky and 100 being completely overcast.

Monthly mean values will have to be calculated and represented in the range of 0.00 to 1.00, that is, 1/100 of the values published in the weather summaries.

Cloud Type: Cloud types are not regularly published and collecting cloud type data is a slow process. Studies using Ottawa data show only slight but systematic variations from one month to another and it was decided that the monthly mean values for Ottawa be used in the simulation.

These values are:

September = 0.70	February = 0.63
October = 0.73	March = 0.62
November = 0.77	April = 0.62
December = 0.78	May = 0.62
January = 0.70	

Air Temperature: Mean daily or monthly air temperature recorded at the nearest climatological station to the site. Input is in degrees Celsius.

Wind Velocity: Average wind velocity for the site in cm/s.

Atmospheric Pressure: The daily or monthly mean station pressure in millibars (mb).

Program Input Data:

Card No.	Program Line No.	Description	Columns Used
1	12	Job title (site, year, etc.)	1-80
2	52	Number of subsurface layers (Pavement, styrofoam, soil, etc.). Maximum of nine.	1
3	86	Label for first layer; index. Index = 0 indicates thermal properties to be read in directly. Index = 1 indicates thermal properties are to be calculated in subroutine SOILS.	
4	89	Index 0. Read in thermal properties.	
		Upper limit, lower limit of layer (cm)	1-4, 5-8
		Water content measured by volume	9-12
		Thermal conductivity, frozen (cal/cm/s/°C)	13-18
		Thermal conductivity, unfrozen	19-24
		Volumetric heat capacity, frozen (cal/cm^3/°C)	25-28
		Volumetric heat capacity, unfrozen	29-32
5	92	Index = 1. Read in soil physical data for calculation of thermal properties.	
		Upper limit, lower limit or layer	1-4, 5-8
		Water Content measured by mass	9-12
		Dry bulk density	13-16
		Percent mass 50 u	17-20

Card No.	Program Line No.	Description	Columns Used
Additional sequences of cards #3 plus #4 *or* #5 for remaining layers.			
6	140	Index indicating whether soil temperature profile is available or not. Index = 0 means not available. Index = n 0 (maximum 50) indicates the number of temperature input points.	1-2
7	144	For input points:	
		Depth below surface (cm)	1-5
		Temperature at this depth (°C)	6-10
		(One card for each depth)	
8	151	Arbitrary initial temperature value. Should be about 3°C higher than mean annual air temperature.	1-5
Note: Ground temperature profile must be initialized by either card #7 or #8.			
9	162	Index indicating if daily or monthly weather data are to be used. Index = 0 means daily values index = 1 means monthly values.	1
10	165	Weather data, daily or monthly mean.	
		Day number	1-2
		Month number	4-5
		Year (only last two digits)	7-8
		Solar radiation	13-16
		Cloud cover	20-22
		Cloud type	24-26
		Air temperature	29-33
		Wind velocity	36-40
		Atmospheric pressure	48-52

In illustration, a complete setup of input cards for the Ottawa Clay Site is included below:

Card No.		Comments
1	Ottawa Highway Sites.....Clay Site 1975/76.....	
2	6	6 layers to be read
3	ASP.O	Asphalt layer with thermal
4	0. 5.0.01.00261.002610.720.72	
3	C11	Soil layer with physical input data
5	5.40. .041.85 94.0	
3	C2 1	
5	40.130. .091.75 87.0	
3	C3 1	
5	130.210. .301.40 32.0	
3	C4 1	
5	210.380. .551.08 25.0	
3	C5 1	
5	380.600. .321.35 71.0	
6	7	7 temperature points to be read
7	0.5	
7.	50. 4.5	
7	100. 6.6	
7	150. 8.6	
7	200. 10.4	
7	250. 12.2	
7	300. 13.0	
8	9.9	No temperature profile available. Initial value set.
9	0	Daily weather data to be used.
10	15.11.74 149. .74 .74 0.6 541. 993.8	
10	16.11.74 98. .68 .80 2.2 434. 1000.5	

VALUES FOR N SUNSHINE HOURS (maximum per day)

Latitude	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
55 N	7.90	9.73	11.87	14.15	16.15	17.27	16.72	14.92	12.73	10.48	8.43	7.28
54 N	8.07	9.82	11.87	14.05	15.98	17.05	16.53	14.80	12.70	10.53	8.57	7.47
53 N	8.22	9.90	11.88	13.98	15.83	16.83	16.35	14.70	12.68	10.60	8.70	7.67
52 N	8.37	9.98	11.88	13.92	15.68	16.63	16.18	14.60	12.67	10.65	8.83	7.85
51 N	8.52	10.05	11.90	13.85	15.55	16.47	16.02	14.52	12.63	10.70	8.95	8.02
50 N	8.63	10.13	11.90	13.78	15.42	16.30	15.87	14.42	12.62	10.75	9.07	8.17
49 N	8.77	10.20	11.90	13.73	15.30	16.15	15.73	14.33	12.60	10.80	9.18	8.32
48 N	8.90	10.27	11.92	13.67	15.18	15.98	15.58	14.27	12.58	10.83	9.28	8.45
47 N	9.00	10.33	11.92	13.62	15.07	15.83	15.45	14.17	12.57	10.88	9.38	8.58
46 N	9.12	10.38	11.92	13.55	14.95	15.67	15.33	14.10	12.55	10.93	9.48	8.72
45 N	9.23	10.45	11.93	13.50	14.85	15.55	15.22	14.03	12.53	10.97	9.58	8.83
44 N	9.33	10.50	11.93	13.45	14.75	15.43	15.10	13.97	12.52	11.00	9.67	8.95
43 N	9.43	10.57	11.93	13.40	14.65	15.30	15.00	13.90	12.50	11.03	9.75	9.07
42 N	9.53	10.62	11.95	13.35	14.57	15.18	14.88	13.83	12.48	11.08	9.83	9.18
41 N	9.62	10.67	11.95	13.32	14.48	15.07	14.78	13.78	12.47	11.12	9.92	9.28
40 N	9.70	10.72	11.95	13.27	14.38	14.97	14.68	13.72	12.47	11.15	9.98	9.38

From Chang (1971)

VALUES FOR Q_A POTENTIAL SOLAR RADIATION

Latitude	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
55 N	149.4	290.8	485.1	723.5	911.1	1005.1	966.0	808.4	584.9	363.8	191.6	118.4
54 N	163.7	305.6	498.4	732.8	915.5	1006.5	968.6	815.3	596.5	378.1	206.2	132.3
53 N	177.9	320.4	511.6	741.9	919.8	1007.9	971.2	822.2	608.1	392.4	220.8	146.1
52 N	192.2	335.3	524.9	751.1	924.1	1009.3	973.7	829.1	619.6	406.8	235.3	160.0
51 N	206.5	350.1	538.1	760.2	928.5	1010.7	976.3	836.0	631.2	421.1	249.9	173.4
50 N	220.8	364.9	551.4	769.4	932.8	1012.1	978.9	842.9	642.8	435.4	264.5	187.7
49 N	235.6	379.4	563.9	777.5	936.3	1013.0	980.8	848.9	653.4	449.2	279.3	202.4
48 N	250.4	394.0	576.3	785.7	939.9	1013.9	982.7	854.9	664.1	463.0	294.1	217.0
47 N	265.3	408.5	588.8	793.8	943.4	1014.7	984.7	860.8	674.7	476.7	309.0	231.7
46 N	280.1	423.1	601.2	802.0	947.0	1015.6	986.6	866.8	685.4	490.5	323.8	246.3
45 N	294.9	437.6	613.7	810.1	950.5	1016.5	988.5	872.8	696.0	504.3	338.6	261.0
44 N	309.9	451.7	625.2	817.1	953.1	1016.5	989.5	877.7	705.6	517.4	353.3	276.0
43 N	324.9	465.8	636.8	824.2	955.6	1016.5	990.5	882.6	715.2	530.5	368.1	291.0
42 N	339.9	479.8	648.3	831.2	958.2	1016.6	991.6	887.5	724.8	543.7	382.8	306.0
41 N	354.9	493.9	659.9	838.3	960.7	1016.6	992.6	892.4	734.4	556.8	397.6	321.0
40 N	369.9	508.0	671.4	845.3	963.3	1016.6	993.6	897.3	744.0	569.9	412.3	336.0

From Chang (1971)

Page 1 of 2

Computer Prediction of Frost Penetration

1. JOB TITLE, Location

2. NUMBER OF LAYERS (max. of 9)

SOILS INFORMATION*

*Fill in either Part A or Part B for each material layer

LAYER NO.	LAYER TYPE	LAYER THICKNESS (cm) TOP	LAYER THICKNESS (cm) BOTTOM	-A- WATER CONTENT by MASS (g/g)	-A- DRY BULK DENSITY g/cm³	-A- PERCENT MASS >50 microns	-B- WATER CONTENT (cm³/g)	-B- THERMAL CONDUCTIVITY, FROZEN cal/cm/sec/°C	-B- THERMAL CONDUCTIVITY, UNFROZEN cal/cm/sec/°C	-B- VOLUMETRIC HEAT CAPACITY, FROZEN cal/cm³/°C	-B- VOLUMETRIC HEAT CAPACITY, UNFROZEN cal/cm³/°C
	1-4	1-4	5-8	9-12	13-16	17-20	9-12	13-18	19-24	25-28	29-32

Page 2 of 2

Climatic Information

FILL IN EITHER A OR B BELOW

A. Set initial Ground Temperature Profile 3°C higher than mean annual air temperature.

B. Initial Ground Temperature Profile from actual thermocouple or thermister readings.

DEPTH BELOW SURFACE (cm)	TEMP. AT THIS DEPTH (°C)

Day	Month	Year	Sunshine Hours	Average Cloud Cover %	Cloud Type	Mean Air Temp. °C	Wind Velocity cm/sec	Atmospheric Pressure kPa
1-2	4-5	7-8	13-16	20-22	24-26	30-33	36-40	48-52

MAIN

```
0001          DIMENSION Z(300),T(300),TC(300),TN(300),XFAC(300)
0002          DIMENSION A(300),B(300),C(300),D(300),BETA(300),GAMMA(300)
0003          DIMENSION LABEL(10),TITLE(20)
0004          DIMENSION ZT(50),TG(50)
0005          DIMENSION FAC(10,3),COND(10,3),VCAP(10,3),LZL(10),VW(10)
0006          REAL KAR2
0007          BB(TK)=8.14E-11*(TK*TK*TK*TK)
0008          TCG(TK)=TK-273.16
0009          TKG(TC)=TC+273.16
        C
        C     ..... READ IN JOB TITLE .....
0010          READ(5,100)(TITLE(I),I=1,20)
0011      100 FORMAT(20A4)
        C
        C     ..... DATA INITIALISATION .....
0012          ALB=0.2
0013          ZO=2.0
0014          FROST=0.0
0015          TPHA=273.16
0016          TPH1=272.16
0017          DT=86400.
0018          FU=80.
0019          ZA=25.E2
0020          KAR2=.16
0021          AIRCAP=.24
0022          XLH=590.
0023          XLHF=670.
0024          XLYD=6.E4*1.44
        C     .... SET GRID SPACING FOR THERMAL DIFFUSION EQUATION........
0025          LST = 300
0026          DZ = 2.0
        C     ..... SET GRID SPACING .....
0027          Z(1)=0.
0028          DO 2 L=2,LST
0029          Z(L)=Z(L-1)+DZ
0030        2 CONTINUE
0031          DZ2=DZ*DZ
0032          ZLAST=(LST-1)*DZ
        C
0033          WRITE(6,200)(TITLE(I),I=1,20)
0034      200 FORMAT(1H1,5X,20A4/)
0035          WRITE(6,201)DT,DZ,LST,ZLAST
0036      201 FORMAT(1H ,5X,'THE FOLLOWING PROBLEM PARAMETERS HAVE BEEN SPECIFIE
             1D:'//10X,'TIME INTERVAL =',E9.3,' SECS'/10X,'GRID SPACING FOR GROU
             2ND TEMPERATURES =',F5.1,' CM'/10X,'NUMBER OF POINTS =',I4/10X,
             3'DEPTH OF LAST POINT =',F7.1,' CM'/)
0037          WRITE(6,202)ALB,ZO
0038      202 FORMAT(1H,5X,'THE FOLLOWING VARIABLES HAVE BEEN SPECIFIED'//10X,'S
             1URFACE ALBEDO =',F5.2/10X,'SURFACE ROUGHNESS =',F5.2)
        C     .....  HOW MANY SUBSURFACE LAYERS? (MAXIMUM NINE)  .....
        C            INCLUDE THE ASPHALT LAYER AS ONE
0039          READ(5,101)NL
0040      101 FORMAT(I1)
0041          WRITE(6,203)NL
0042      203 FORMAT(1H0,5X,'THE FOLLOWING SUBSURFACE CONDITIONS HAVE BEEN SPECI
             1FIED:'/10X,'NUMBER OF LAYERS =',I2/)
0043          WRITE(6,204)
0044      204 FORMAT(1H ,41X,'THERMAL PROPERTIES'//30X,'VOL.LAT.',
             18X,'FROZEN',10X,'THAWED'/10X,'#',3X,'NAME',4X,'DEPTH',
             25X,' HEAT',6X,'COND',3X,'VOLCAP',3X,'COND',3X,'VOLCAP')
        C     ..... SOIL DATA INPUT SECTION .....
        C     ..... READ IN SOIL INFORMATION BY LAYER .....
        C           YOU MAY ENTER THERMAL PROPERTIES DIRECTLY, OR HAVE
        C           THEM CALCULATED IN SUBROUTINE SOILS. THIS OPTION IS
        C           VARIABLE BY LAYER, SO THAT THE INPUT MODE MAY
        C           DIFFER BY LAYER.
        C           FOR EACH LAYER THERE IS ONE PAIR OF CARDS:
        C                ON THE FIRST CARD IS A LABEL (SOIL TYPE),
        C                FOLLOWED BY A CODE INDICATING THE TYPE OF
        C                INPUT DATA FOR THAT LAYER:
        C                     0 INDICATES THAT THERMAL PROPERTIES ARE
        C                     TO BE READ IN DIRECTLY. THESE ARE:
        C                          THE DEPTH INTERVAL (ZU,ZL)
        C                          VOLUMETRIC WATER CONTENT (VW)
        C                          THERMAL CONDUCTIVITY (FROZEN, UNFROZEN)
        C                          VOLUMETRIC HEAT CAPACITY (FROZEN,
        C                                                    UNFROZEN)
        C                     1 INDICATES THAT THERMAL PROPERTIES ARE
        C                     TO BE CALCULATED ON THE BASIS OF
        C                     PHYSICAL INFORMATION SUPPLIED. THIS IS:
        C                          THE DEPTH INTERVAL (ZU,ZL)
        C                          GRAVIMETRIC WATER CONTENT (W)
        C                          BULK DENSITY (BD)
        C                          PERCENT SAND (SAND)
0045          DO 3 I=1,NL
0046          READ(5,103)LABEL(I),IS
0047      103 FORMAT(A4,I1)
0048          IF(IS.EQ.1) GO TO 5
0049          READ(5,105)ZU,ZL,VW(I),COND(I,1),COND(I,3),VCAP(I,1),VCAP(I,3)
0050      105 FORMAT(2F4.0,F4.2,2F6.5,2F4.2)
0051          GO TO 15
0052        5 READ(5,106)ZU,ZL,W,BD,SAND
0053      106 FORMAT(2F4.0,2F4.2,F4.0)
0054          CALL SOILS(W,BD,SAND,COND(I,1),COND(I,3),VCAP(I,1),VCAP(I,3),VW(I)
             *)
```

```
0055          15 LZL(I)=ZL/DZ
0056             LZU=ZU
0057             LZ=ZL
0058             VLH=VW(I)*FU
0059             WRITE(6,205)I,LABEL(I),LZU,LZ,VLH,COND(I,1),VCAP(I,1),
                1COND(I,3),VCAP(I,3)
0060           3 CCNTINUE
0061         205 FORMAT(1H ,9X,I1,3X,A4,3X,I3,'-',I3,3X,F5.2,5X,F6.5,2X,F4.2,4X,F6.
                15,3X,F4.2)
0062             WRITE(6,214)
0063         214 FORMAT(1H0,9X,'UNITS FOR THERMAL PROPERTIES ARE AS FOLLOWS'/15X,
                1'VOLUMETRIC LATENT HEAT   = CAL/CU CM'/15X,'THERMAL CONDUCTIVITY
                2   = CAL/CM/DEG/SEC'/15X,'VOLUMETRIC HEAT CAPACITY = CAL/CU CM')
0064             WRITE(6,215)
0065         215 FORMAT(1H1,5X,'THIS IS A LIST OF SYMBOLS USED IN THE FOLLOWING PRI
                *NTOUT'/10X,'RS: INCOMING SOLAR RADIATION (LY/DAY)'/10X,'CLOUD: CLO
                2UD COVER (DECIMAL FRACTION)'/10X,'TYPE: CLOUD TYPE (SEE PROGRAM DE
                3SCRIPTION)'/10X,'TEMP: AIR TEMPERATURE (DEG C)'/10X,'WIND: WINDSPE
                *ED (CM/SEC)'/10X,'PRESS: ATMOSPHERIC PRESSURE (MB)'/
                6                    //10X,'RSN: ABSORBED SOLAR RADIATION AT SURFACE (
                7LY/DAY)'/10X,'RLN: EFFECTIVE OUTGOING LONGWAVE RADIATION FROM SURF
                8ACE'/10X,'RN: NET RADIATION BALANCE'/10X,'S: SOIL HEAT FLUX (NEGAT
                *IVE SIGN INDICATES FLUX INTO THE SOIL)'/10X,'H: SENSIBLE HEAT FLUX
                * INTO THE AIR (NEGATIVE SIGN INDICATES UPWARD FLUX)')
0066             WRITE(6,206)
0067         206 FORMAT(1H1)
        C
        C         SET VALUES IN THERMAL DIFFUSION MATRIX
        C         CODE: FAC(N,N)
        C               CODE N: SOIL LAYER NUMBER
        C               CODE N: 1-FROZEN, 2-PHASE, 3-UNFROZEN
0068             DO 10 I=1,NL
0069             FAC(I,1)=CCND(I,1)*DT/VCAP(I,1)
0070             FAC(I,2)=COND(I,1)*DT/( VW(I)*FU+(VCAP(I,1)+VCAP(I,3))/2.)
0071             FAC(I,3)=CCND(I,3)*DT/VCAP(I,3)
0072          10 CONTINUE
        C
        C        ..... INITIALISE GROUND TEMPERATURE MATRIX .....
        C               IF YOU HAVE GROUND TEMPERATURE INPUT,
        C               ENTER THE NUMBER OF POINTS (MAX 50).
        C               READ IN DEPTH (CM) AND TEMPERATURE (C) - ONE PAIR PER CARD
        C        ..... IF YOU HAVE NO GROUND TEMPERATURE INPUT, ENTER 0
        C               FOLLOW THIS WITH ANOTHER CARD CONTAINING SOME
        C               ARBITRARY INITIAL VALUE
0073             READ(5,104)NZ
0074         104 FORMAT(I2)
0075             IF(NZ.EQ.0) GO TO 20
0076             DO 18 I=1,NZ
0077          18 READ(5,107)ZT(I),TG(I)
0078         107 FORMAT(2F5.1)
0079             CALL INTERP(ZT,TG,Z,1.E-4,NZ,LST,T)
0080             DO 19 L=1,LST
0081             T(L)=TKG(T(L))
0082          19 CONTINUE
0083             GO TO 25
0084          20 READ(5,107)TBAR
0085             DO 21 L=1,LST
0086             T(L)=TKG(TBAR)
0087          21 CONTINUE
        C
0088          25 CONTINUE
        C
0089             TEQ=T(1)
        C        ..... ENTER CODE FOR TYPE OF WEATHER DATA INPUT .....
        C               FOR DAILY INPUT, ENTER 0
        C               FOR MONTHLY INPUT, ENTER 1
0090             READ(5,108)IDATA
0091         108 FORMAT(I1)
0092             IF(IDATA.EQ.0) GO TO 35
0093             READ(5,109)IDAY,MON1,IY1,SUN1,CLO1,CC1,TA1,UA1,P1
0094             MO=MON1
0095             IYR=IY1
0096          32 READ(5,109,END=999)IDAY,MON2,IY2,SUN2,CLO2,CC2,TA2,UA2,P2
0097             IDAY=15
0098             DIF1=(SUN2-SUN1)/30.0
0099             DIF2=(CLO2-CLO1)/30.0
0100             DIF3=(CC2-CC1)/30.0
0101             DIF4=(TA2-TA1)/30.0
0102             DIF5=(UA2-UA1)/30.0
0103             DIF6=(P2-P1)/30.0
0104             ITIME=0
0105          33 SUN=SUN1+DIF1*FLOAT(ITIME)
0106             CLO=CLO1+DIF2*FLOAT(ITIME)
0107             CC=CC1+DIF3*FLOAT(ITIME)
0108             TA=TA1+DIF4*FLOAT(ITIME)
0109             UA=UA1+DIF5*FLOAT(ITIME)
0110             P=P1+DIF6*FLOAT(ITIME)
0111             IF(MO.EQ.12.AND.IDAY.GT.30)IYR=IY2
0112             IF (IDAY .GT. 30) MO = MON2
0113             IF(IDAY.GT.30)IDAY=IDAY-30
0114             GO TO 38
0115          35 READ(5,109,END=999)IDAY,MO,IYR,SUN,CLO,CC,TA,UA,P
0116          38 CONTINUE
0117             WRITE(6,207)IDAY,MO,IYR,SUN,CLO,CC,TA,UA,P
0118         109 FORMAT(I3,I2,1X,I2,4X,F4.0,2X,F4.2,F4.2,2X,F5.1,2X,F5.0,7X,F5.0)
```

```
0119          207 FORMAT(1H0,'DATE=',I2,'/',I2,'/',I2/1H0,2X,'RS =',F5.0,2X,'CLOUD =
                 1',F4.2,2X,'TYPE =',F4.2,2X,'TEMP =',F6.1,2X,'WIND =',F6.0,2X,
                 2'PRESS =',F6.0)
0120              LEQ=1.
            C
            C     ..... EQUILIBRIUM SURFACE TEMPERATURE SOLUTION .....
0121              TAK=TKG(TA)
0122              AIRDEN=.34838*(P/TAK)*1.E-3
0123              RSN=SUN*(1.-ALB)
0124              CF=1.0-CC*CLO*CLO
0125              KOUNT=0
0126              G1=TAK-20.
0127              G2=TAK+20.
0128              BAL=1.E20
0129              GO TO 44
0130           41 G2=TEQ
0131              GO TO 44
0132           43 IF(BAL.LT.0.) GO TO 41
0133              G1=TEQ
0134           44 TEQ=(G1+G2)/2.
0135              RLA=BB(TAK)*(1.0-0.261*EXP((-7.77E-4)*(273.2-TAK)**2))
0136              RLN=CF*(BB(TEQ)-RLA)
0137              RLN=RLN*1440.
0138              RN=RSN-RLN
0139              IF (TEQ .LE. TPHA) GO TO 51
0140              CK=COND(1,3)
0141              GO TO 50
0142           51 CK = COND(1,1)
0143           50 CONTINUE
0144              S=(CK/DZ)*(T(LEQ+1)-TEQ)*XLYD
0145              CALL HFLUX(TAK,TEQ,ZA,ZO,UA,P,AIRDEN,H)
0146              BAL=RN+S+H
0147              TEST=ABS(BAL)
0148              KOUNT=KOUNT+1
0149              IF (KOUNT.GT.100) GO TO 58
0150              IF (TEST.GT.1.) GO TO 43
0151              GO TO 59
0152           58 CONTINUE
0153              WRITE(6,208)
0154          208 FORMAT(10X,'NO EQUILIBRIUM TEMP. SOLUTION')
0155           59 CONTINUE
0156           70 CONTINUE
0157              TDIF=TEQ-TAK
0158              IF(ABS(TDIF).LE.5.0)GO TO 80
0159              IF (TEQ .LT. TAK) GO TO 81
0160              TEQ=TAK+5.0
0161              GO TO 80
0162           81 TEQ = TAK - 5.0
0163           80 CONTINUE
            C
            C     ..... THERMAL DIFFUSION IN SOIL .......
0164              FROST=0.0
0165              T(1)=TEQ
0166              L1=LEQ+1
0167              L=LST-1
0168              DO 130 I=L1,L
0169              N=2
0170              DO 122 IL=1,NL
0171              IF (I .LE. LZL (IL)) GO TO 123
0172          122 CONTINUE
0173          123 M = IL
0174              IF (T (I) .GT. TPHA) GO TO 134
0175              IF (T(I).LT.TPH1) N=1
0176              IF(T(I-1).GE.TPHA)N=2
0177              GO TO 135
0178          134 N = 3
0179          135 XFAC(I)=FAC(M,N)/DZ2
0180              A(I)=-XFAC(I)
0181              B(I)=1.0+2.0*XFAC(I)
0182              C(I)=-XFAC(I)
0183              D(I)=T(I)
0184          130 CONTINUE
0185              D(L1)=D(L1)+XFAC(L1)*T(LEQ)
0186              D(L)=D(L)+XFAC(L)*T(LST)
0187              BETA(L1)=B(L1)
0188              GAMMA(L1)=D(L1)/BETA(L1)
0189              L1P1=L1+1
0190              DO 140 I=L1P1,L
0191              BETA(I)=B(I)-A(I)*C(I-1)/BETA(I-1)
0192          140 GAMMA(I)=(D(I)-A(I)*GAMMA(I-1))/BETA(I)
0193              TN(L)=GAMMA(L)
0194              TN(LEQ)=T(LEQ)
0195              TN(LST)=T(LST)
0196              LAST=L-L1
0197              DO 150 K=1,LAST
0198              I=L-K
0199              TN(I)=GAMMA(I)-C(I)*TN(I+1)/BETA(I)
            C     ..... FROST DEPTH SEARCH .....
0200              IF(T(I-1).LE.TPHA.AND.T(I).GT.TPHA)GO TO 141
0201              GO TO 142
0202          141 RATIO=ABS((T(I-1)-TPHA)/(T(I-1)-T(I)))
0203              FROST=(FLOAT(I-2)+RATIO)*DZ
0204          142 CONTINUE
            C
0205              IF(I.GT.27) GO TO 145
0206              IF (TN( 1).GT.TPHA) GO TO 145
```

```
0207          IF(TN(I).LT.TPHA.OR.TN(I).GT.277.) GO TO 145
0208          IF (TN(I-1).LT.TN(I)) GO TO 145
0209          TN(I)=(TN(I-1)+TN(I))/2.
0210          IF(TN(I).GT.T(I))TN(I)=T(I)
0211      145 CONTINUE
0212      150 CONTINUE
0213          TN(LST)=T(LST)
0214          DO 160 L=1,LST
0215          T(L)=TN(L)
0216      160 CONTINUE
        C
0217          DO 170 L=1,LST
0218          TC(L)=TCG(T(L))
0219      170 CONTINUE
0220          WRITE(6,209)ZO,ALB,RSN,RLN,RN,S,H,TC(LEQ),FROST
0221      209 FORMAT(1H0,2X,'SURFACE ROUGNESS =',F6.2,3X,'SURFACE ALBEDO =',F5.2
             1/3X,'RSN =',F6.1,4X,'RLN =',F6.1,4X,'RN =',F7.1/3X,'S=',F6.1,4X,'H
             2 =',F6.1,4X /3X,'SURFACE TEMPERATURE =',F6.1,4X,'FROST DEPTH =',F6
             3.1,' CM')
0222          WRITE(6,210)
0223      210 FORMAT(1H0,2X,'DEPTH',8X,'GROUND TEMPERATURE MATRIX')
0224          DO 220 K=1,6
0225          IDEPTH=(K-1)*100
0226          KL=(K-1)*50+1
0227          KU=KL+49
0228          WRITE(6,211)IDEPTH,(TC(L),L=KL,KU,5)
0229      220 CONTINUE
0230          IDEPTH=600
0231          WRITE(6,211)IDEPTH,TC(LST)
0232      211 FORMAT(1H,2X,I3,4X,10F6.1)
0233          WRITE(6,212)
0234      212 FORMAT(1H0)
        C
0235          DO 250 L=1,LST
0236          TC(L)=0.0
0237      250 CONTINUE
0238          IF(IDATA.EQ.0)GO TO 35
0239          IDAY=IDAY+1
0240          ITIME=ITIME+1
0241          IF(ITIME.EQ.30)GO TO 998
0242          GO TO 33
0243      998 MON1=MON2
0244          IY1=IY2
0245          SUN1=SUN2
0246          CLO1=CLO2
0247          CC1=CC2
0248          TA1=TA2
0249          UA1=UA2
0250          P1=P2
0251          GO TO 32
0252      999 CONTINUE
0253          STOP
0254          END
```

SOILS

```
0001          SUBROUTINE SOILS(W,B,S,CONDF,CONDU,VCAPF,VCAPU,VW)
        C     ..............SUBROUTINE SOILS.......................
        C     .....CALCULATES THERMAL CONDUCTIVITY AND VOL. HEAT CAPACITY ....
        C      ....FROM INPUT=BULK DENSITY,WATER CONT. AND PERCENT SAND.......
0002          VW=W*B
0003          B=B*62.428
0004          W=W*100.
0005          IF(S-50.)90,80,80
        C     .....THERMAL CONDUCT. FOR PERCENT SAND>50.........
        C     .....THERMAL COND. FOR SOIL ,PERCENT SAND<50.............
0006       80 CONDF=0.076*10.**(0.013*B)+0.032*10.**(0.0146*B)*W
0007          CONDF=CONDF*0.00413/12.
0008          V=ALOG10(W)
0009          CONDU=(0.7*V+0.4)*10.**(0.01*B)
0010          CONDU=CONDU*0.00413/12.
        C      .......HEAT CAP. IF PERCENT SAND > 60 ..........
0011          IF(S.GT.60.0)GO TO 96
0012          AC=0.01*10.**(0.022*B)+0.085*10.**(0.008*B)*W
0013          AC=AC*0.00413/12
0014          CONDF=(CONDF+AC)/2.
0015          BC=(0.9*V-0.2)*10.**(0.01*B)
0016          BC=BC*0.00413/12.
0017          CONDU=(CONDU+BC)/2.
0018          GO TO 96
0019       90 CONDF=0.01*10.**(0.022*B)+0.085*10.**(0.008*B)*W
0020          CONDF=CONDF*0.00413/12.
0021          V=ALOG10(W)
0022          CONDU=(0.9*V-0.2)*10.**(0.01*B)
0023          CONDU=CONDU*0.00413/12.
0024       96 W=W/100.
0025          B=B/62.428
0026          X1=W*B
0027          PO=1.-B/2.65
0028          X3=1.-PO
0029          VCAPF=(X1+X3)*0.46
0030          VCAPU=X1+X3*0.46
0031      100 CONTINUE
0032          RETURN
0033          END
```

HFLUX

```
0001          SUBROUTINE HFLUX(TA,T,ZA,ZO,U,PR,AR,H)
0002          VK=0.4
0003          G=980.
0004          CP=.24
0005          CPD=AR*CP
0006          XLYD=6.E4*1.44
0007          DRYADB=-1.E-4
0008          TBAR=0.5*(TA+T)
0009          TGRAD=(TA+DRYADB*ZA-T)/ALOG(ZA/ZO)
0010          UGRAD=U/ALOG(ZA/ZO)
0011          ZBAR=SQRT(ZA*ZO)
0012          RI=(G/TBAR)*ZBAR*(TGRAD/(UGRAD**2))
0013          IF(RI)5,10,15
0014        5 BL=ZBAR/RI
0015          X1=(1.-(16.*ZO/BL))**.25
0016          X2=(1.-(16.*ZA/BL))**.25
0017          PS11=2.*ALOG(.5*(1.+X1))+ALOG(.5*(1.+X1*X1))-2.*ATAN(X1)+3.1416/2.
0018          PS12=2.*ALOG(.5*(1.+X2))+ALOG(.5*(1.+X2*X2))-2.*ATAN(X2)+3.1416/2.
0019          PS21=2.*ALOG(.5*(1.+X1*X1))
0020          PS22=2.*ALOG(.5*(1.+X2*X2))
0021          GO TO 20
0022       10 PS11=0.
0023          PS12=0.
0024          PS21=0.
0025          PS22=0.
0026          GO TO 20
0027       15 BL=ZBAR*(1.-7.*RI)/RI
0028          PS11=7.*ZC/BL
0029          PS12=7.*ZA/BL
0030          PS21=PS11
0031          PS22=PS12
0032       20 XX1=ALOG(ZA/ZO)-PS12
0033          XT1=ALOG(ZA/ZO)-PS22
0034          BUS=VK*U/XX1
0035          BTHS=(TA+DRYADB*ZA-T)/XT1
0036          H=CPD*VK*BUS*BTHS*XLYD
0037          RETURN
0038          END
```

INTERP

```
0001          SUBROUTINE INTERP(X,Y,T,EPSLN,N,M,SS)                                  405
0002          DIMENSION H(50),DELY(50),X(50),Y(50),T(200),B(50),DELSQY(50),          406
             *S2(50),C(50),S3(50),H2(50),SS(200),SS2(200)                            407
0003          KOUNT=0                                                                408
        C THIS INTERPOLATION REQUIRES ASCENDING VALUES OF X                          409
0004          NN=N-1                                                          409A
0005          DO 100 I=1,NN                                                   410
0006          IF(X(I+1).LT.X(I)) GO TO 101                                           411
0007          IF(X(I+1).EQ.X(I)) GO TO 102                                           412
0008          IF(T(I).LT.X(1)) GO TO 305                                      413
0009          GO TO 100                                                       413A
0010      305 SS(I)=Y(1)                                                      413B
0011          KOUNT=KOUNT+1                                                   413C
0012      100 CONTINUE                                                               414
0013        2 N1 = N - 1                                                             415
0014        3 DO 51 I = 1,N1                                                         416
0015          H(I) = X(I+1) - X(I)                                                   417
0016       51 DELY(I) = (Y(I+1) - Y(I))/H(I)                                         418
0017        4 DO 52 I = 2,N1                                                         419
0018          H2(I) = H(I-1) + H(I)                                                  420
0019          B(I) = .5*H(I-1)/H2(I)                                                 421
0020          DELSQY(I) = (DELY(I) - DELY(I-1))/H2(I)                                422
0021          S2(I) = 2.*DELSQY(I)                                                   423
0022       52 C(I) = 3.*DELSQY(I)                                                    424
0023          S2(1) = 0.                                                             425
0024          S2(N) = 0.                                                             426
0025          OMEGA = 1.0717968                                                      427
0026        5 ETA = 0.                                                               428
0027        6 DO 10 I = 2,N1                                                         429
0028        7 W=(C(I)-B(I)*S2(I-1)-(.5-B(I))*S2(I+1)-S2(I))*OMEGA                    430
0029        8 IF (ABS(W)-ETA)10,10,9                                                 431
0030        9 ETA = ABS(W)                                                           432
0031       10 S2(I) = S2(I) + W                                                      433
0032       13 IF (ETA - EPSLN) 14,5,5                                                434
0033       14 DO 53 I = 1,N1                                                         435
0034       53 S3(I) = (S2(I+1)-S2(I))/H(I)                                           436
0035       15 JJ=KOUNT+1                                                       437
0036          DO 61 J=JJ,M                                                    437A
0037          IF(T(J).GT.X(N)) GO TO 306                                      438
0038          GO TO 16                                                        438A
0039      306 SS(J)=Y(N)                                                      438B
0040          GO TO 61                                                        438C
0041       16 I = 1                                                                  439
0042       54 IF(T(J) -X(1))58,17,55                                                 440
0043       55 IF(T(J)-X(N))57,59,58                                                  441
0044       56 IF(T(J)-X(I))60,17,57                                                  442
0045       57 I = I+1                                                                443
0046          GO TO 56                                                               444
0047       58 WRITE(6,44)J                                                           445
0048       44 FORMAT(I4,'24HTH ARGUMENT OUT OF RANGE'                                446
0049          GO TO 61                                                               447
0050       59 I = N                                                                  448
0051       60 I = I-1                                                                449
0052       17 HT1 = T(J)-X(I)                                                        450
0053          HT2 = T(J) - X(I+1)                                                    451
0054          PROD = HT1*HT2                                                         452
0055          SS2(J)=S2(I)+HT1*S3(I)                                                 453
0056          DELSQS = (S2(I)+S2(I+1)+SS2(J))/6.                                     454
```

Ontario

Ministry of
Transportation and
Communications

Policy
Planning and
Research Division

Aspects of Prolonged Exposure of Pavements to Sub-Zero Temperatures

Part 2
The Val Gagne Pavement Insulation Experiment

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Abstract

Since the first successful treatment of a frost heave problem in 1966 using STYROFOAM™ HI brand extruded polystyrene foam insulation, Ontario has used substantial quantities of insulation. However, knowledge of the performance of the insulation has been limited to sparsely documented observations of some differently insulated sites. In 1972, a joint experiment was launched by the Ministry of Transportation and Communications and the Dow Chemical Company of Canada Limited to construct, instrument, and observe the performance of pavement insulation at Val Gagne in Ontario.

Three thicknesses of insulation were used in the experiment, and four different taper designs. Winter temperature profiles, frost penetration depths, and frost heave measurements were observed during the winters of 1973 to 1977. The results of these observations were used to verify a two–dimensional finite element heat flow computer program intended for use in the design of insulation for controlling frost penetration. While the program accurately predicts ground temperature for uninsulated situations and thin insulated sections, changes in the program are needed to correct inaccuracies in prediction for thick insulations.

The results were also used in the development of a set of frost penetration prediction curves under various thicknesses of insulation and at locations with different degree–days of freezing temperatures. These curves may be used to select the appropriate insulation thickness for any acceptable depth of frost penetration.

STYROFOAM™ insulation recovered from the test site after five years shows virtually no structural changes or changes in thermal properties.

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1/Introduction

Differential frost heaving poses serious potential safety hazards (Figure 1) and has perennial after–effects on highways located in the northern areas of the United States and Canada. Prior to 1966, all treatments of frost heaves in Ontario involved removal of the frost susceptible soil to great depths and/or ditching and drainage to remove entrapped water and to lower the water table. These treatments were not always successful.

Research into the use of STYROFOAM™ for highway insulation began in the United States in the early 1960s, and by 1965 several full–scale experimental projects had been constructed [1, 2, 3, 4]. These early research sites were instrumented with thermocouples and frost depth indicators to measure the insulating properties of various thicknesses of STYROFOAM™ insulation. The first major research sites in Canada were constructed near Winnipeg on the Trans–Canada Highway in 1962, and near Sudbury in 1966 [5]. The findings of these early studies have resulted in the present widespread use of STYROFOAM™ in areas that have sufficient frost penetration to make differential frost heaving a significant problem.

Since the 1970s, Ontario has been using increasing amounts of STYROFOAM™ HI brand extruded polystyrene foam insulation for frost heave treatments in the northern part of the province. The reasons for this are two–fold:

1/ Experience has shown that correctly designed STYROFOAM™ always works to prevent recurrence of the frost heave, whereas, other more conventional treatments may or may not be successful.

2/ Cost comparisons of the various alternatives tend to show STYROFOAM™ as being the most economical treatment.

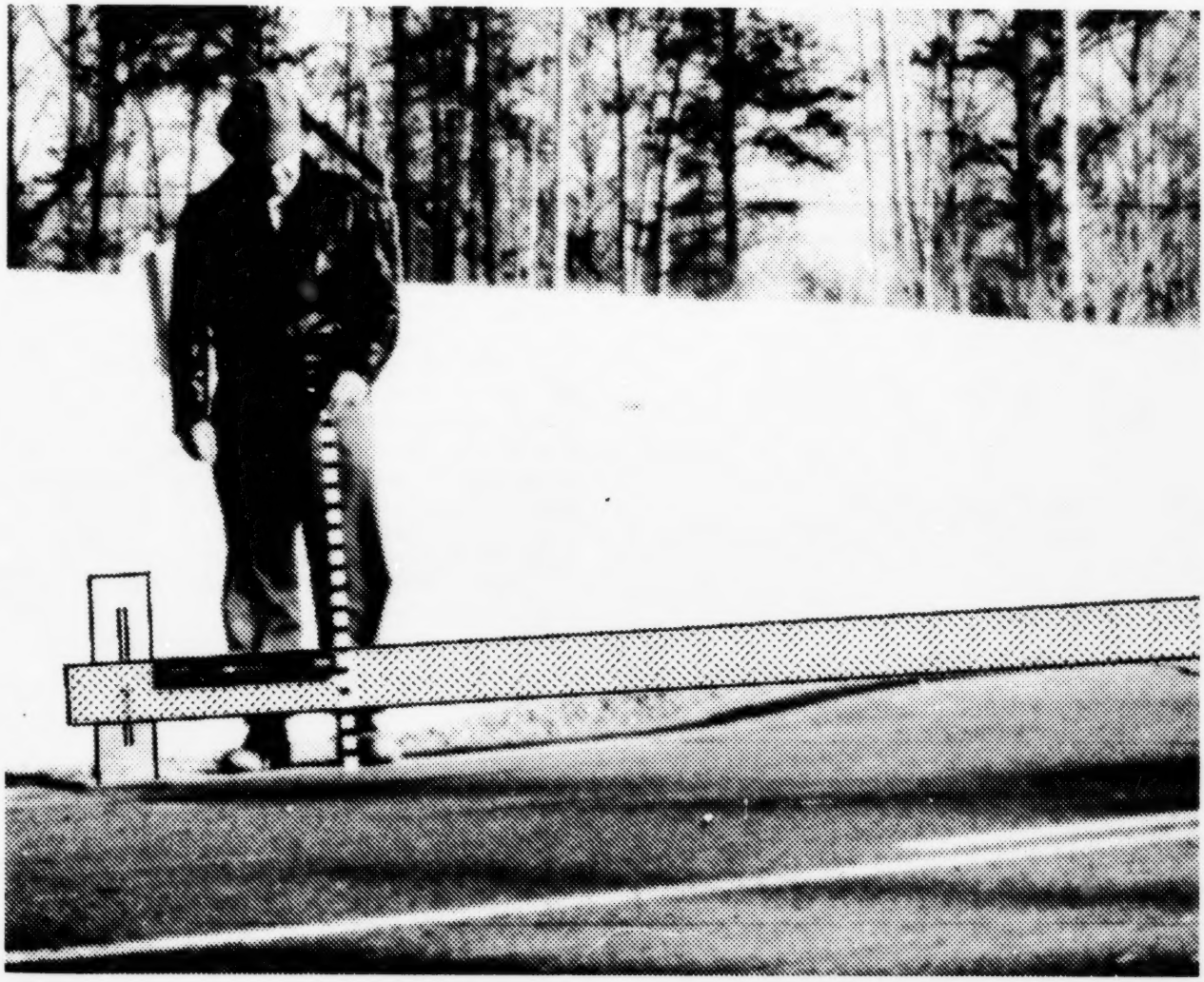
In Ontario, highway insulation has been adopted by the Ministry as an economical treatment for differential frost heaving. By 1972 the province was using approximately 3500 m^3 of STYROFOAM™ per year [6] for treating frost heaves.

The thicknesses of STYROFOAM™ used in early installations depended on the number of degree–days of frost at the heave location. The rule of thumb used in the design of these treatments was 25 mm of STYROFOAM™ for each 555 degree–days Celsius of frost to prevent frost penetration. Through a trial and observation approach, some of the variables such as minimum depth of granular over STYROFOAM™ and desired taper lengths were determined and incorporated in a set of design standards based on the best performing installations. Studies into the use of STYROFOAM™ for highway insulation have been continued in recent years by regional staff, essentially in the form of close observation of the performance of numerous installations.

In 1971, the Ministry and Dow Chemical of Canada Limited jointly constructed a full–scale insulation research installation principally to investigate the most effective utilization methods for the insulation. This experiment was constructed during the summer of 1972 at Val Gagne located 65 km south of Cochrane. The basic ex-

periment involved the use of three thicknesses of STYROFOAM™ HI–35 covered with 460 mm of granular and 75 mm of asphaltic concrete. Full instrumentation was installed to measure ambient and ground temperatures, pavement elevations (frost heave) and frost penetrations. This report details the construction, instrumentation and results of this five–year study (1972 to 1977).

Figure 1/ Typical Frost Heave Considered for Treatment with STYROFOAM™



2/Goals and Objectives

The objectives behind the setting up of the Val Gagne test site were to attempt to find solutions to problems in the current design standards.

The overall goals were to minimize specific problems presently encountered with insulation through the evaluation of data from an experimental installation.

The long term goal was to best utilize insulation materials in highway construction from both an economical and technical viewpoint.

The following objectives formed the basis of the site's design:

2.1/Pavement Heaving

In certain insulated sections completed in recent years, a differential frost heave had occurred at the transition from insulated to non–insulated sections. Several theories have been put forward to explain this problem but none are based on scientific data. From heave measurements taken in the three STYROFOAM™ thicknesses used, as well as through the transition zones, it may be possible to minimize or eliminate the differential heave now associated with insulated sections.

2.2/Depth of Frost Penetration

When STYROFOAM™ was first used for insulation of highways, it was thought that to be effective, the thickness should be sufficient as to stop all frost penetration below the STYROFOAM™ layer. One of the prime objectives was to measure the depth of frost penetration in an area of 1850 degree–days Celsius of frost or greater under varying thicknesses of insulation.

The information obtained will permit designs with controlled frost penetration below the STYROFOAM™ layer.

2.3/Long Term Effects of Subgrade Insulation

The effect of STYROFOAM™ insulation on the long term thermal regime below the layer is not clearly understood. The heat flow from the subgrade upwards is prevented during the winter months; however, the insulation also restricts heat flow into the ground during the summertime. It is possible that the seasonal fluctuation of temperature will be restricted below the STYROFOAM™ layer and the mean annual ground temperature may change due to the altered heat flow characteristics. The research site will hopefully shed some light on this subject.

2.4/Pavement Icing

The occurence of pavement differential icing over insulated sections in the fall and occasionally in the spring of the year when surface moisture is available presents a potential serious hazard to the motorist. The altered heat flow properties in these areas keeps the moisture frozen over the treated pavement. It was intended at this site to closely monitor the three test sections, but, due to the site location only haphazard icing observations were possible and icing is not dealt with further in this report.

2.5/Frost Depth Indicator Reliability
Fifteen modified Swedish frost depth indicators [7] were installed in various locations throughout the site. Several of the indicators were placed within 0.6 m of the thermocouple sets. The comparison between the thermocouple readings and the frost depth indicator measurement will provide a check on the reliability of the indicators.

2.6/Layer Width
The experiment will contribute to the knowledge of thermal conditions at the edge of insulation treatments and provide guidance in considering the possibility of reducing design widths.

2.7/Computer Prediction Model
Dow engineers have recently developed a two dimensional finite element computer model for prediction of heat flow characteristics in pavement design. This site will provide verification of the prediction accuracy of the program under the extreme environmental conditions which are experienced in northern Ontario.

2.8/Durability of STYROFOAM™
The durability of STYROFOAM™ used for pavement insulation will be studied from samples taken after five years of use.

3/Layout of the Experiment

The test site is located on Highway 11 in the Cochrane District (Figure 2) approximately 3.2 km north of the junction of Highway 101.

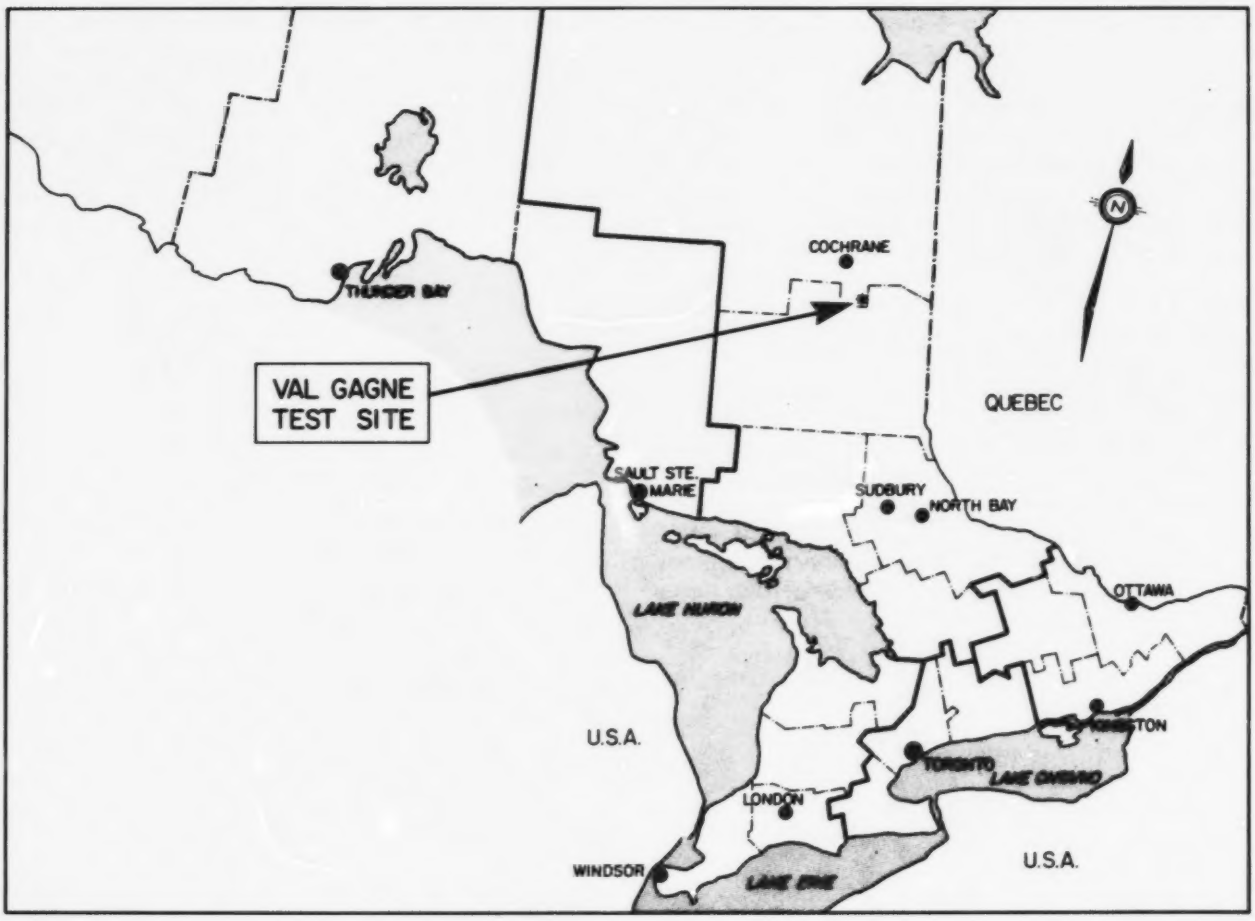
The site was selected for several reasons:

(1) The pavement at this location did not experience an abrupt or hazardous heave but rather a general distortion during the winter months.

(2) The Val Gagne area regularly experiences severe winter weather with freezing indices of 1833 degree–days Celsius or greater. Frost indicator measurements have shown that penetration to a depth of 2.4 m to 3.0 m is common [7].

(3) The roadway was constructed as a 1.2 m to 1.5 m cut through a heavy, clay soil. This cut is uniform in depth throughout the site as the original ground profile has the same slope as the pavement.

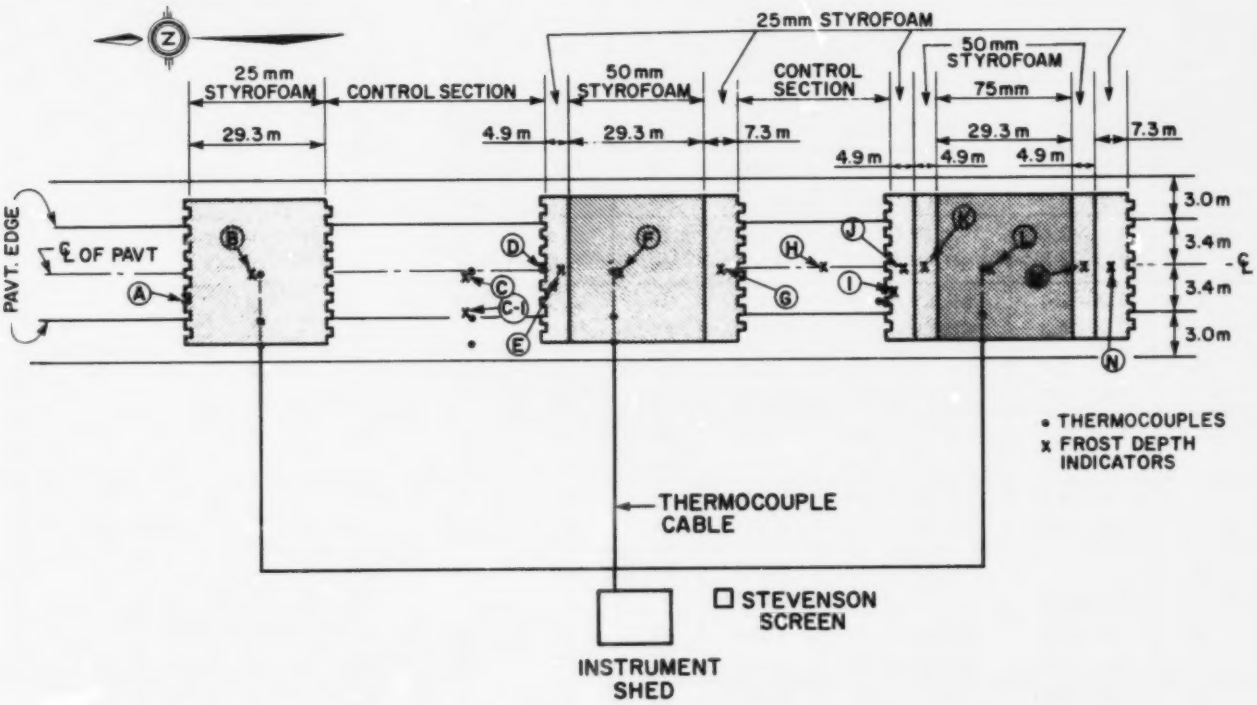
Figure 2/ The Val Gagne Test Site



(4) The site is 65 km south of the Cochrane District office which allows relatively easy access by staff assigned to take regular weekly measurements during the fall, winter and spring.

(5) The experiment was designed to evaluate three different thicknesses of STYROFOAM™, 25 mm, 50 mm and 75 mm. Each section is 29.2 m in length plus transitions, and is separated from each other by non–insulated control sections. Figure 3 shows the site layout.

Figure 3/ Val Gagne Test Site Layout



4/Soils

Soil samples were obtained for various depths throughout the test site [8]. The field work consisted of 10 sample boreholes. Four boreholes were taken 1.7 m east of the centreline. All boreholes were taken using a hollow–stemmed auger.

The laboratory tests on the soil samples have shown that the stratigraphy at the test site consists of a 100 mm layer of asphalt pavement on approximately 900 mm of granular underlain by a wet–to–saturated varved clay soil.

The subgrade soils at the site are mainly fat and gumbo clays. This soil is classified as CH soil according to the Unified Soil Classification System, or an A–7–6 type soil as specified by the AASHTO Soil System. This soil has a very high plasticity index and a liquid limit greater than 50%. The water content of the silty clay soil ranged from 22% to 67%. The water table was 1.2 m below the pavement surface in three boreholes.

Under the Unified Soil Classification System, CH (silty clay) soil is considered to be a frost susceptible soil since more than half of the fine grained aggregate contained in the clay passes the #200 sieve.

Results of the tests taken on the subgrade soil are given in Table 1.

Table 1/ Physical Properties of the Subgrade Soils at the Time of Construction

BORE HOLE NUMBER	ELEVATION DEPTH BELOW PAVEMENT (metres)	MATERIAL NAME	DRY/ DENSITY t/m³	WATER CONTENT (%)	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	PLASTICITY INDEX (%)	CLASSIFICATION	
								A.A.S.H.O. SOIL	UNIFIED SOIL
1	1.5 – 2.4	SILTY CLAY	1.314	38	58	34	24	A – 7 – 5	MH–OH
	2.4 – 4.6	SILTY CLAY	0.977	63	62	25	37	A – 7 – 6	CH
2	1.5 – 2.4	SILTY CLAY	1.698	22	51	26	25	A – 7 – 5	CH
	2.4 – 4.6	SILTY CLAY	1.073	52	59	29	30	A – 7 – 6	CH
3	1.5 – 2.4	SILTY CLAY	1.666	15	34	25	9	A – 7 – 6	ML–OL
	2.4 – 4.6	SILTY CLAY	0.961	66	66	28	38	A – 7 – 6	CH
4	1.5 – 2.4	SILTY CLAY	1.426	31	58	27	31	A – 7 – 6	CH
	2.4 – 4.0	SILTY CLAY	0.993	62	64	28	36	A – 7 – 6	CH
5	1.5 – 2.4	SILTY CLAY	1.281	38	62	28	34	A – 7 – 6	CH
	2.4 – 4.6	SILTY CLAY	0.977	64	68	27	41	A – 7 – 6	CH
6	1.5 – 2.4	SILTY CLAY	1.041	59	65	27	38	A – 7 – 6	CH
	2.4 – 4.6	SILTY CLAY	1.041	55	57	27	30	A – 7 – 6	CH
7	1.5 – 2.4	SILTY CLAY	1.458	27	58	28	30	A – 7 – 6	CH
	2.4 – 4.6	SILTY CLAY	0.977	63	67	27	40	A – 7 – 6	CH
8	1.5 – 2.4	SILTY CLAY	0.993	62	66	27	39	A – 7 – 6	CH
	2.4 – 4.6	SILTY CLAY	0.961	67	67	22	45	A – 7 – 6	CH
9	1.5 – 2.4	SILTY CLAY	1.234	47	64	28	36	A – 7 – 6	CH
	2.4 – 4.6	SILTY CLAY	0.977	63	59	29	30	A – 7 – 6	CH
10	1.5 – 2.4	SILTY CLAY	1.458	31	52	23	29	A – 7 – 5	CH
	2.4 – 4.6	SILTY CLAY	0.961	66	70	29	31	A – 7 – 6	CH

5/Design and Construction

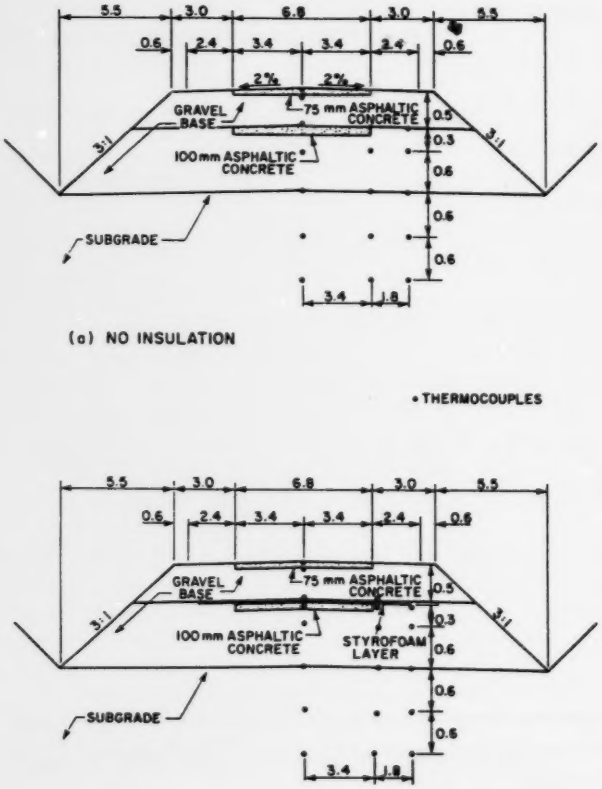
Design of the test sections was in accordance with the Ministry's standards SD–4–86, 87 and 91 [9] except for the taper lengths on the southern end of both the 50 mm and 75 mm sections. The width of the STYROFOAM™ layer was extended 1.8 m beyond the pavement edge (Figure 4).

The 50 mm thick section had the normal 4.9 m transition on the northern or uphill end and a longer 7.3 m length of 25 mm insulation on the other end (Figure 3). A longer 12.2 m transition consisting of 4.9 m of 50 mm and 7.3 m of 25 mm foam was placed at the southern end of the 75 mm section. The normal 9.8 m transition was used at the other end.

The 2.40 m by 0.60 m STYROFOAM™ boards of the required thickness were laid directly on the old pavement surface after a light tack coat of emulsion had been applied to the surface by hand spray. Shovels filled with granular base material were placed on the STYROFOAM™ boards to prevent movement during the subsequent operation (Figure 5).

The granular base material was end dumped at the beginning of the STYROFOAM™ layer and spread in a thick layer by a small bulldozer over the length of the section. With this construction method, there is minimal displacement of the STYROFOAM™ sheets. A minimum layer thickness of 310 mm of granular material is placed on top of the STYROFOAM™ to prevent its damage by subsequent compaction and other operations by construction equipment. The completed sections were brought up to profile grade with a total lift of 460 mm of granular cover and then paved with 75 mm of HL–4 asphaltic concrete. A more detailed description of the construction is contained in Reference 10.

Figrue 4/ Typical Cross Sections, Uninsulated and STYROFOAM™ Insulated Sections Showing Thermocouple Locations



Note: All dimensions are in metres unless otherwise specified.

6/Instrumentation

Full site instrumentation was installed to measure ambient ground temperatures, frost penetration and pavement heaving. Ground temperatures were taken by the use of 21 copper constantan thermocouples installed in each insulated section and control section. The thermocouples were arranged in three vertical strings with one set placed at the centreline, one at the edge of pavement and one at the edge of the STYROFOAM™ layer. The strings have thermocouples at the following depths: top and bottom of the pavement, above the STYROFOAM,™ below the STYROFOAM,™ 0.3 m below the STYROFOAM™ and three at 0.61 m intervals below that. A total of 84 thermocouples were installed in this way (Figures 4 and 6).

In addition to this, three thermocouples were placed in the 25 mm transition of the 75 mm section; one thermocouple was located under a finger, one between the fingers, and one off the end of the finger. (In transitions, every other sheet is extended beyond the body of the insulation, and is called a finger.)

Figure 5/ Construction of the STYROFOAM™ Insulated Sections

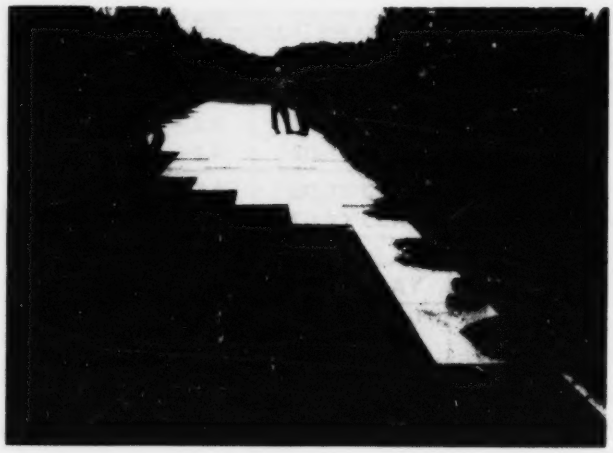


Figure 6/ Thermocouples Being Installed

Originally the thermocouple wires were run into wooden boxes mounted on posts by the edge of the shoulder, and rotary switches were used to connect the individual thermocouples to the readout potentiometer for measurements. This method was used during the 1972–73 winter season. However, thermocouple readings taken at different times during this period were found to be inconsistent and erratic. It was felt that the problem was condensation forming inside the switch boxes when they were moved from their unheated wooden boxes into a warm vehicle interior for the measurements to be taken. To solve this problem, a heated utility shed (1.8 m by 2.4 m) was erected on site and all thermocouples led into this building. No problems were encountered after this change, and the majority of thermocouples continued to operate normally.

During the summer of 1973, a Stephenson screen and thermohydrograph were installed on site to make possible continuous recording of both ambient air temperature and relative humidity.

Fifteen frost depth indicators of the modified Swedish type were located throughout the site (Figures 3 and 7). They were installed in the middle of each section with some being placed in the tapers in order to measure frost penetration through this critical area. These frost depth indicators have been used by the Ministry for several years and are an inexpensive and efficient way to measure frost depth.

In order to facilitate accurate monitoring of the heaving movements occurring throughout the test site, approximately 700 nails were placed in the pavement (Figure 8 & 9). These nails were set in epoxy in pre–drilled holes in the pavement surface. Two benchmarks were also placed in the pavement at the site. These benchmarks are founded well below the maximum frost depth and consist of steel rods in outer telescoping casings, to ensure that the elevation will remain constant throughout the years. A geodetic benchmark located near the site will provide an accurate datum for all measured elevations.

The nails were spaced at 1.2 m longitudinal intervals throughout the site. Through all transition areas, the nails were spaced longitudinally 0.61 m apart extending 6.1 m in each direction beyond the transitions. Three rows were placed in this manner at the transitions — along centreline, and in the centre of each lane.

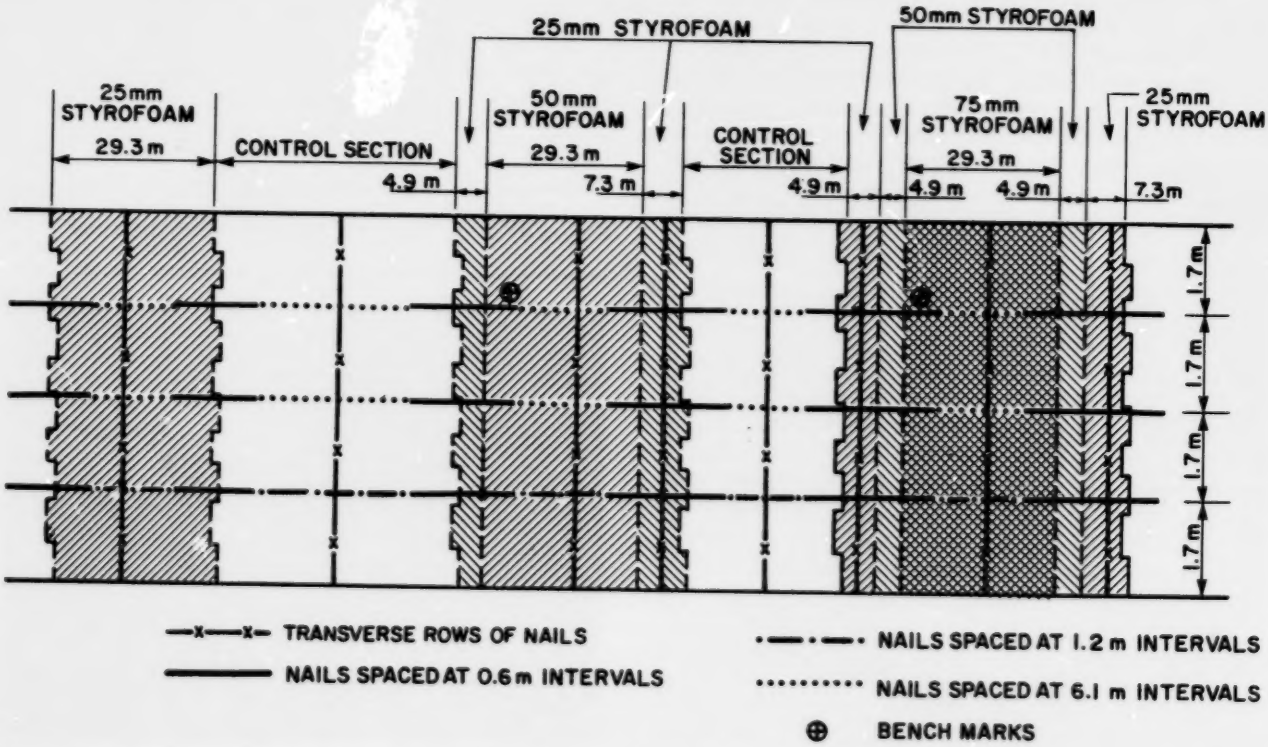
Figure 7/ Frost Depth Indicators Being Installed

6.1/Measurement Frequency

A five–year period of observation of the test site has been completed. During this time, the thermocouples were normally read weekly during the frost season and at monthly intervals over the summer months. Frost depth indicators were normally read weekly when any ground frost was present. Four sets of elevations on the nails were taken yearly, every fall before any frost enters the ground, at mid–winter, during the spring thaw and mid–summer.

Figure 8/ Overall View of the Test Site Showing Levelling Nails and Instrument Shed

Figure 9/ Levelling Nails and Benchmark Layout

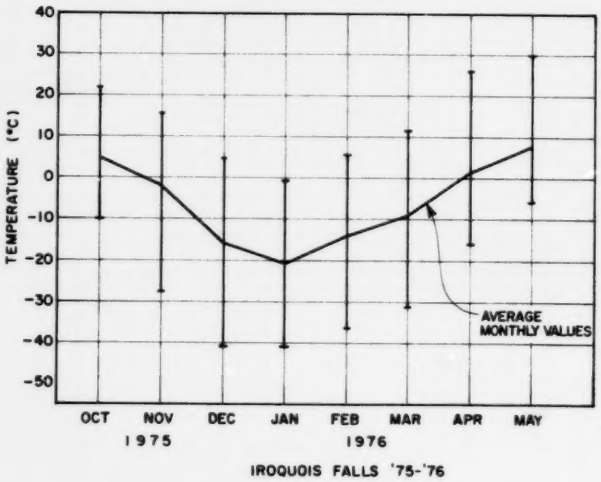


7/Temperature and Precipitation

Only 290 km north of the Val Gagne test site lie the shores of James Bay and arctic tidewater. With an average annual air temperature of only 1°C [11] and winter temperatures often dropping to below –40°C, severe winters are not an uncommon experience. Ambient air temperatures and precipitation for the site were obtained from the Environment Canada Climatological Station at Iroquois Falls, located approximately 24 km to the northeast. Additional backup data was available from the station in Cochrane and on–site data was provided by the thermohydrograph installed in 1973. An indication of the type of weather found at this site is shown in Figure 10 in which the average monthly temperatures and ranges recorded at Iroquois Falls station are plotted.

Freezing indices calculated using the mean daily air temperatures as well as the coldest recorded air temperatures in each of the five years are tabulated in Table 2.

Figure 10/ Typical Monthly Maximum and Minimum Temperatures Recorded at Iroquois Falls 1975-1976



The weather during the five–year test period ranged from a very severe winter experienced during 1973–1974 to the relatively mild winter of 1974–1975. This range provided a good test for the materials and their performance under varying climatic conditions.

Table 3 lists the monthly precipitation recorded at Iroquois Falls during the test period.

Year	Climatological Station			
	Iroquois Falls		Cochrane	
	Degree-Days °C	Lowest Temp °C	Degree-Days °C	Lowest Temp °C
1972 – 1973	1810	-41	1805	-44
1973 – 1974	2097	-40	2209	-45
1974 – 1975	1659	-40	1783	-42
1975 – 1976	2038	-42	2124	-46
1976 – 1977	1849	-38	2080	-39
5-Year Mean	1891	-	2000	-
30-Year Mean	1882*	-	1838*	-
Design Freezing Index	2097	-	2209	-

*Reference [11]

Table 2/ Freezing Indices and Lowest Recorded Temperatures Taken from the Nearest Climatological Stations

Table 3/ Precipitation over the Five Year Test Period Taken at Iroquois Falls Climatological Station

YEAR	JAN		FEB.		MAR.		APR.		MAY		JUNE		JULY		AUG.		SEPT.		OCT.		NOV.		DEC.		TOTAL	
	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S
1972		71.4		25.4	1	7.11	7	3.8	61	17.8	103		77		87		71		65	4.1	29	17.8		50.0	50.1	261.4
1973	10	26.4		39.9	77		40	2.0	72	5.8	65		70		99		117		64		20	14.0		45.5	634	133.6
1974		56.6		35.1	13	20.1	17	54.1	63	9.7	71		122		113		106		74		10	6.4		52.1	589	234.1
1975	19	52.8	9	16.5			41	7.6	70		9		70		60		77		53		34	57.9	18	40.6	460	175.4
1976		64.8		26.2	41	55.4	53	22.9	36	7.6	43		56		59		62		33	9.1		35.3		58.7	383	280.0

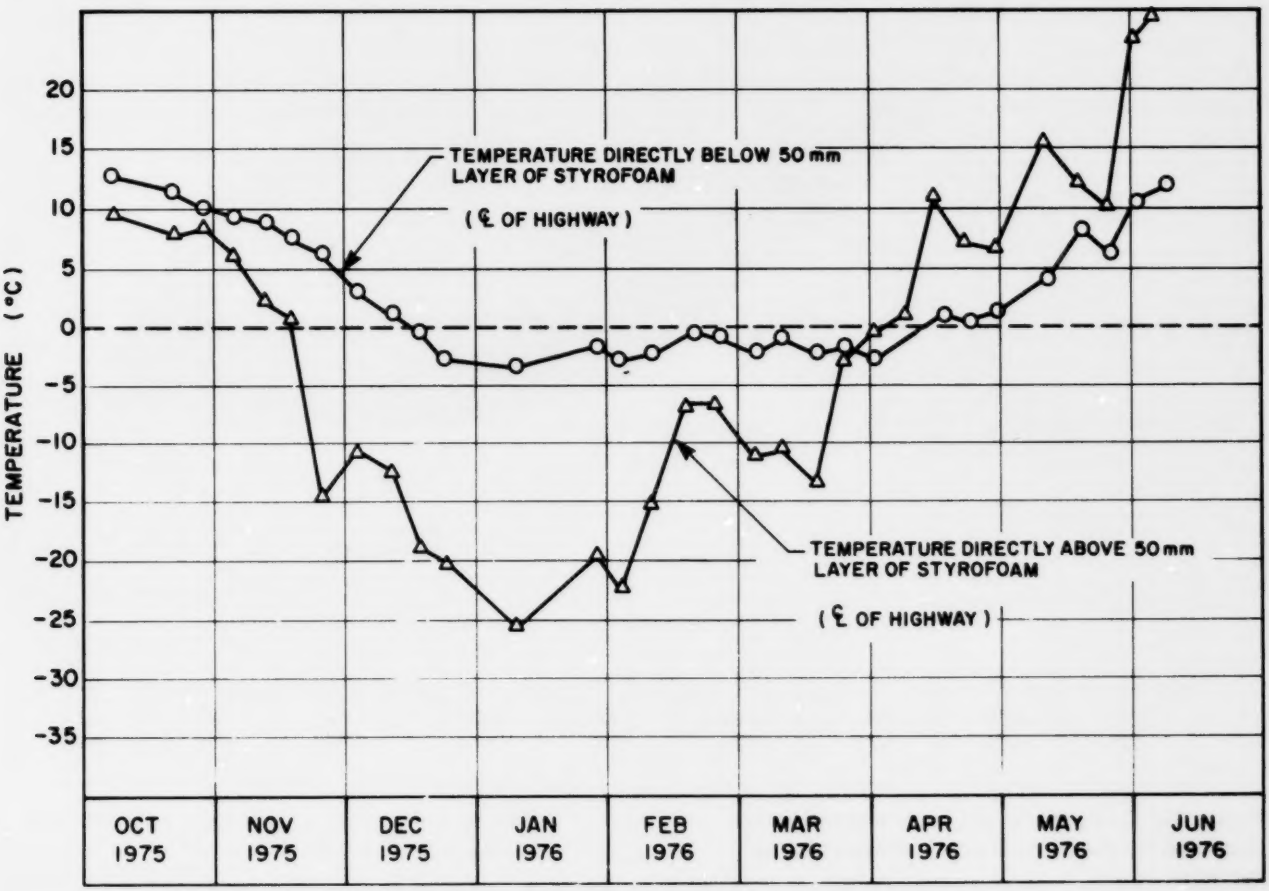
R – RAILFALL MILLIMETRES
S – SNOWFALL CENTIMETRES

8/Ground Temperatures

Temperatures in each section were taken at various depths (Figure 4) by the use of thermocouples. During the winter months temperatures above the insulation are usually considerably lower than those below. This temperature difference increases with greater insulation thickness. A typical example of temperatures taken above and below the 50 mm insulation layer is illustrated in Figure 11.

Complete results of temperature measurements are reported in references 12, 13, 14.

Figure 11/ Typical Temperatures Taken Directly Above and Below the 50 mm Layer of Insulation at the Centreline



9/Frost Penetration Time Profile

Frost penetration can be determined through interpolation of the thermocouple readings or by direct reading from the frost indicators. Figure 12 shows typical time–depth patterns of frost penetrations, as determined by frost indicators at the pavement centreline in all sections. The insulating effect of the STYROFOAM™ layer is clearly illustrated, with increasing thickness of STYROFOAM™ leading to reduced frost penetration. Frost penetration, as recorded by the indicators for all sections over the five years, is summarized in Table 4. Greater depths of frost were recorded in each succeeding year except for the very mild winter of 1974-1975. The reason for this continuously increasing penetration is not known although it may be partially due to the lowering of subsoil temperatures under the STYROFOAM™ layer, or by changes in subsoil moisture conditions. While there was a slight increase in moisture content of the STYROFOAM™ (loss in insulating value), this would not account for the continuous increase.

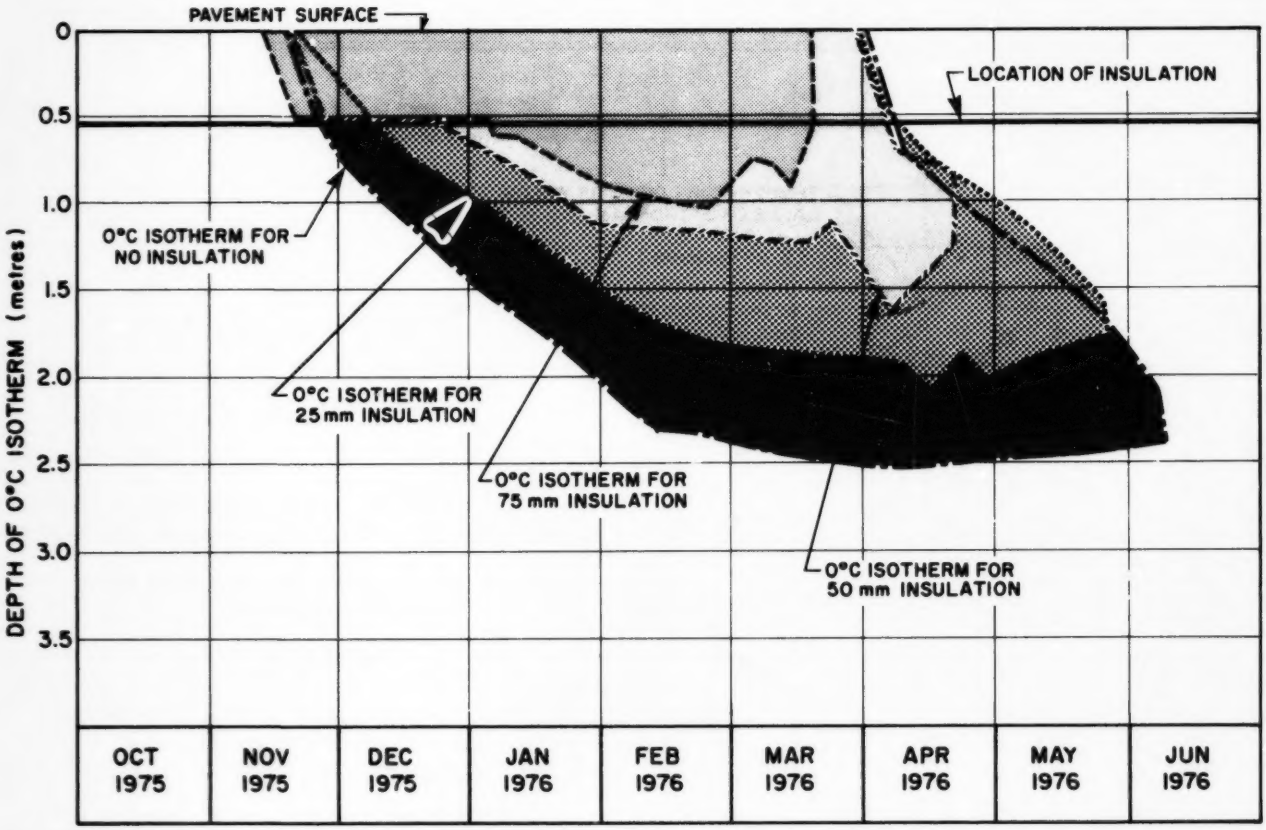


Figure 12/ Comparison of Frost Penetration as Recorded by the Frost Depth Indicators for all Sections

Table 4/ Maximum Frost Penetration in Metres as Measured by the Frost Depth Indicators

	Frost Penetration in Metres				
Section	**1972-73**	**1973-74**	**1974-75**	**1975-76**	**1976-77**
Control no insultation	2.36	2.49	2.39	2.59	2.62
25 mm insulation	1.60 (1.07)	1.73 (1.20)	1.60 (1.07)	1.90 (1.37)	2.03 (1.50)
50 mm insulation	1.02 (0.49)	1.14 (0.61)	1.12 (0.59)	1.22 (0.69)	1.42 (0.89)
75 mm insulation	0.58 (0.05)	0.94 (0.41)	0.68 (0.15)	1.02 (0.49)	1.09 (0.56)

Numbers in parenthesis are measurements taken below the STYROFOAM layer.

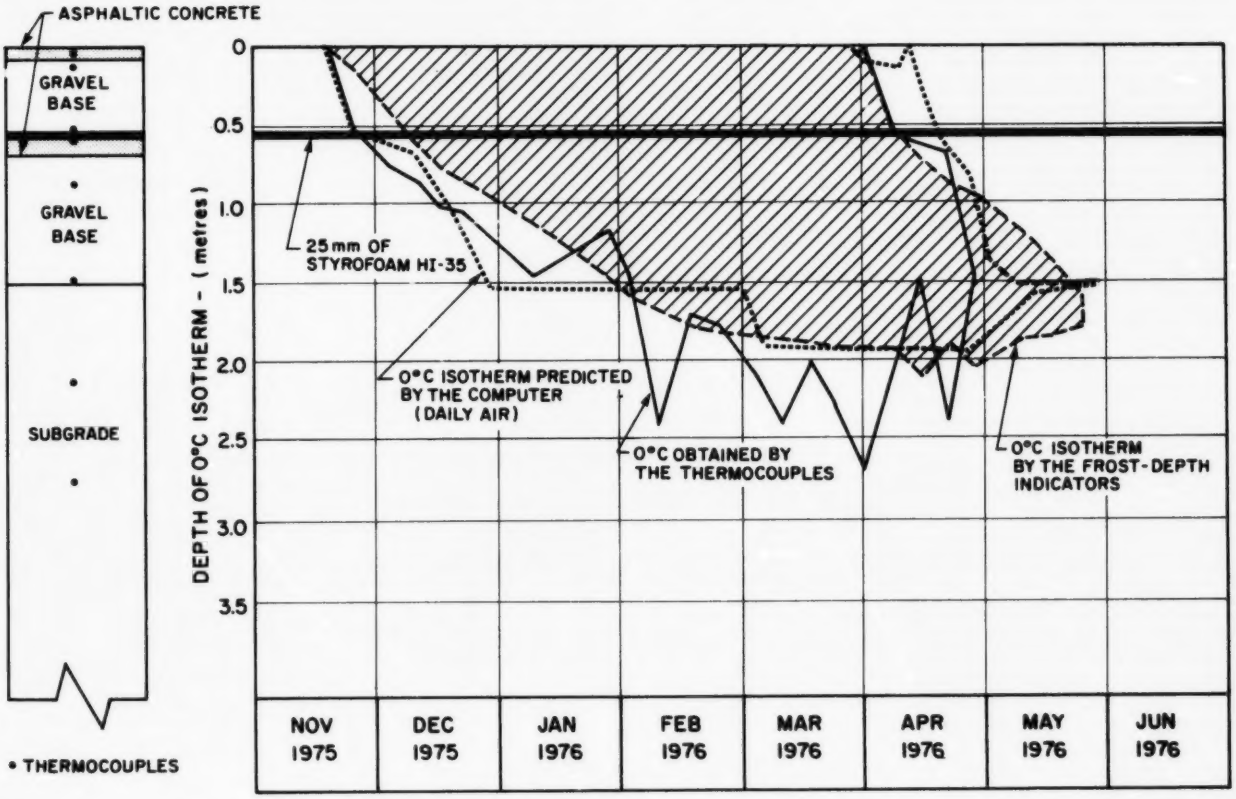


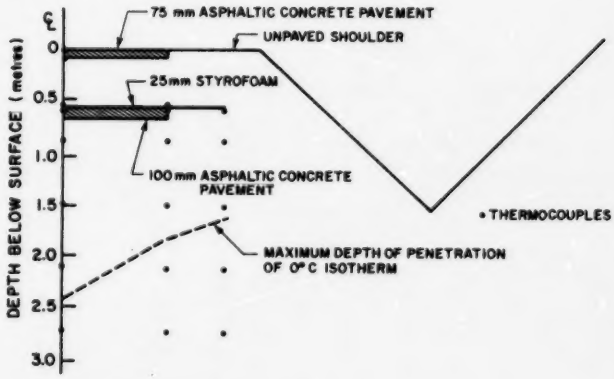
Figure 13/ Maximum Depths of Frost Penetration Recorded at the Centreline of the 25 mm Section During 1973-1974

It is important to note that some thermocouple data was too erratic for establishing the 0°C isotherm. An example of this is shown in Figure 13, where the frost penetration below the 25 mm layer of STYROFOAM® fluctuated from about 1.02 m on March 15 to 2.46 m on March 28. This rapid change in only a two week period is highly unlikely and this suggests that errors were occuring either in instrument calibration or readout. The frost depth indicator on the other hand, with its simplicity of design and use, shows a more consistent and logical progression of the freezing front.

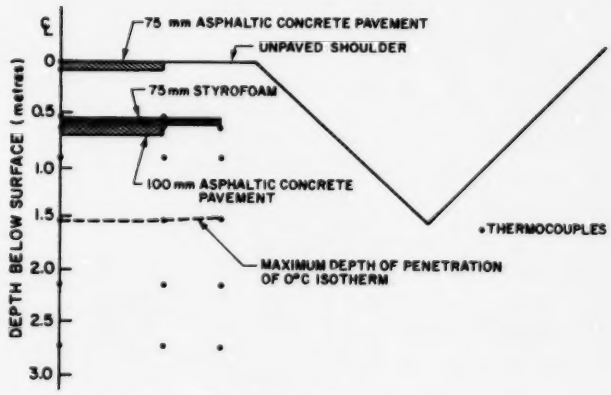
9.1/Transverse Cross Section of Frost Penetration

The depths of frost penetration as measured transversely across each section are illustrated in Figure 14. In both the uninsulated and 25 mm sections, the depths of the 0°C isotherm as recorded by the thermocouples were much lower below the pavement surface at the centreline than at the edges of the embankment. This heat gain can be attributed to the insulating effect of

Figure 14/ Transverse Cross Section of Maximum Frost Penetration (1975-1976)



(a) 25 mm INSULATED SECTION



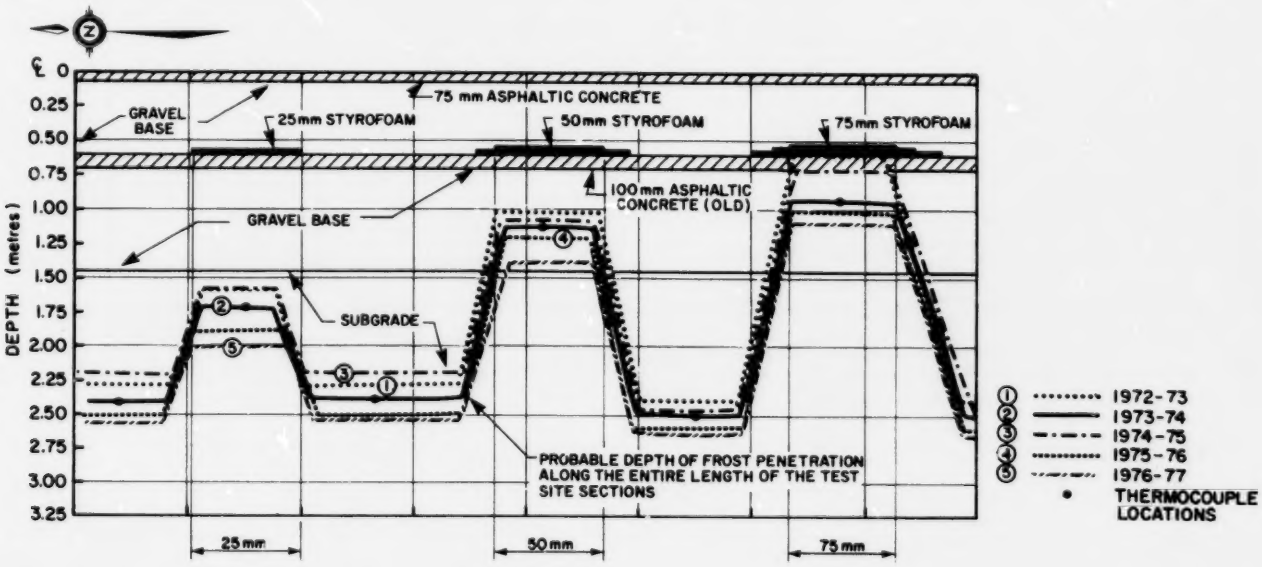
(b) 75 mm INSULATED SECTION

the snow accumulated on the shoulders and ditches of the highway embankment. In the 50 mm and 75 mm sections, the 0°C isotherms recorded below the insulating layers were roughly parallel to the roadway surface.

9.2/Maximum Frost Penetration

The maximum frost penetration recorded for each of the five years in the test sections and transitions along the length of the site are shown in Figure 15. The freezing front reached into the frost susceptible subgrade soil under the 25 mm section every year. Only during the 1976–77 winter did the frost level under the 50 mm section come within a few inches of the subgrade. The frost level in the 75 mm insulated section remained well within the gravel base layer in all years.

Figure 15/ Maximum Depths of Frost Penetration Throughout the Test Site During the Five Year Test Period



10/Frost Heaving

Soil conditions at this site did not lead to unusual or severe differential frost heaving. In general, during the more severe winters, the uninsulated sections of roadway heaved approximately 24 mm to 40 mm. This compares with heaves ranging from 0.0 mm to 6 mm in the 75 mm sections and 8 mm to 24 mm in the 25 mm section. Table 5 lists the average heave for each section during the five-year test period. The slight bumps that did occur over the transition areas were never great enough to adversely affect the riding comfort over the test sections. Figure 16 illustrates the results at the centreline of surface measurements on both the insulated and uninsulated sections for the year 73–74, 74–75 and 75–76. Further information such as heave profiles is shown for centreline and midlanes in references 12, 13, 14.

10.1/Transverse Heaves

Heave measurements taken transversely across the pavement clearly show the difference in heaving between the insulated and uninsulated sections. The pavement edge tends to heave more than the centre of the pavement possibly due to water penetrating under the pavement edge. Typical results of the transverse heave measurements are shown in Figure 17. The heave is negligible over the 50 mm and 75 mm layers of STYROFOAM.™

Figure 16/ Frost Heave Measurement Taken at the Pavement Centreline

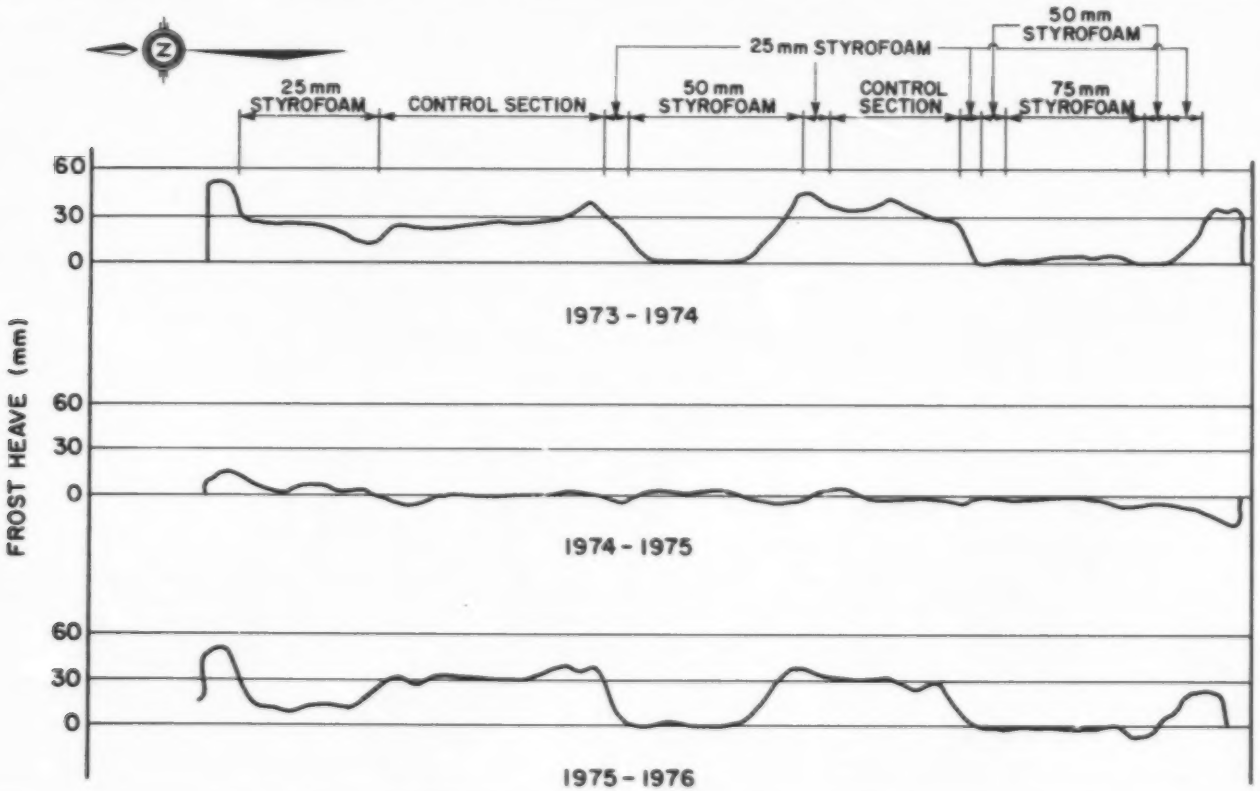


Table 5/ Average Heave Measured at the Centreline (mm)

Section	1972-73	1973-74	1974-75	1975-76	1976-77
Control no insultation	30	37	0	34	18
25 mm insulation	9	24	3	9	2
50 mm insulation	0	6	3	3	0
75 mm insulation	0	6	0	3	0

10.2/Transition Heaves

The transition tapers on the southern end of the 50 mm and 75 mm sections were lengthened to try to provide a more gradual transition from the insulated sections (which move relatively less) to the non–insulated portion of the highway (which moves relatively large amounts).

Differential heaving was not a problem at this site as gradual changes rather than abrupt

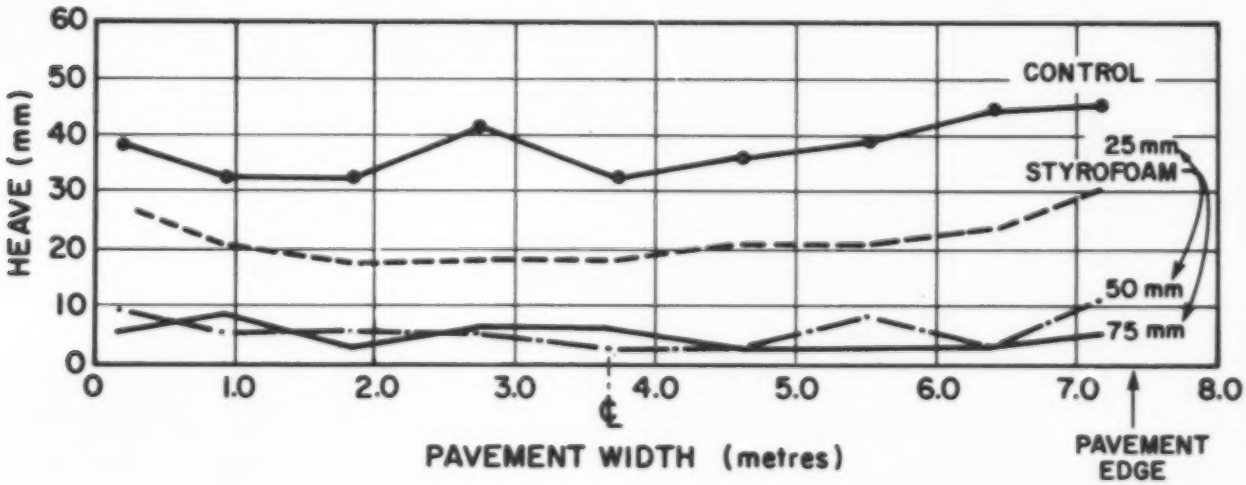


Figure 17/ Typical Heave Recorded in the Transverse Direction (1973-1974)

heaves occurred at all transitions. It appears from the slope of the transition that the 50 mm section with the 7.3 m transition is better than the 4.9 m transition used on the north end. On the 75 mm section, no improvement was observed with the 12.2 m taper used on the south end over the standard 9.8 m taper on the north side. Figure 18 illustrates the 1973–74 heaves through the transition areas.

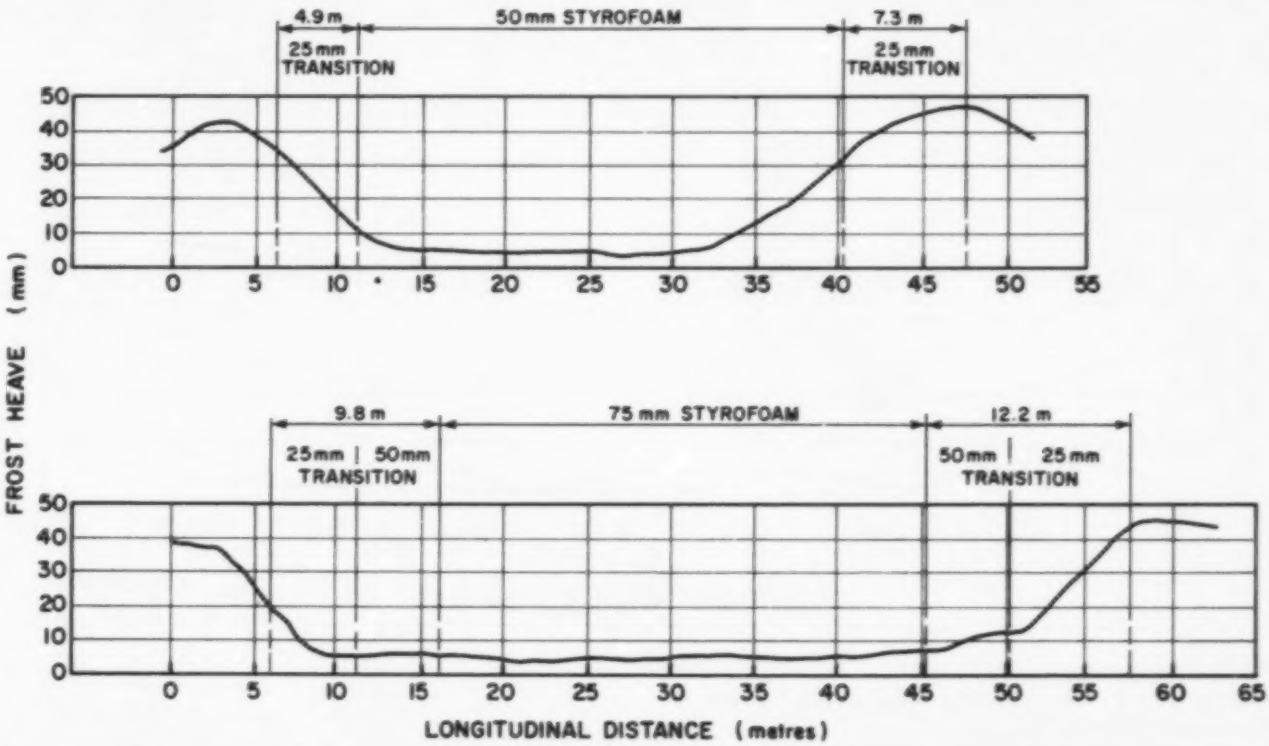
11/Long Term Subgrade Temperature Regime

One objective of this study was to ascertain if long term temperature changes were occurring in the subgrade below the STYROFOAM™ sections.

Table 6 compares the subgrade temperatures of each STYROFOAM™ section in relation to the uninsulated control section.

Measurements taken at 0.86 m below the surface show that the soil temperatures do not fluctuate as much from season to season as in the control sections. Data from the deepest thermocouples at 2.69 m exhibit a similar trend although the temperature difference between the insulated and uninsulated sections increases as STYROFOAM™ thickness increases. The effects on the pavement structure of this temperature variance are not completely known, however, moisture migration effects may be one area which should be explored more fully.

Figure 18/ Longitudinal Heaving Through the Transition Areas (1973-1974)



12/Subgrade Moisture Conditions

A detailed foundation investigation report (8) on the subsoil conditions found at the test site was completed by the Ministry's Soils Mechanics Section before construction began in 1972. In September 1976, the Geotechnical Office of Northern Region carried out another series of sampling and tests to determine if subgrade moisture conditions had changed as a result of the insulation being a part of the pavement structure. However, the accuracy of these latter results appears questionable because of the sampling method, therefore, no conclusions have been drawn for moisture movement.

13/Pavement Cracking

In northern Ontario, thermally induced transverse cracks are prevalent. A crack survey taken on the 75 mm pavement over the test sections exhibited this same pattern (Figure 19). Some centreline construction–joint cracks were also present. There was no significant difference between sections, as all insulated and non–insulated had major cracks both in the body of the section and in the transition areas. The uniform crack patterns do not reveal any differences in performance due to different thicknesses of insulation.

Table 6/ Changes in Subgrade Temperature as Compared to the Uninsulated (Control) Section Temperatures (°C)

Thermocouple Location	THERMOCOUPLE READING 0.86 m below Surface				THERMOCOUPLE READING 2.85 m below Surface			
		Temp. Difference from Control Section				Temp. Difference from Control Section		
Date	Control Actual Temp °C	25 mm Section	50 mm Section	75 mm Section	Control Actual Temp °C	25 mm Section	50 mm Section	75 mm Section
August 1973	22	-4	-7	-8	16	-4	-6	-6
February 1974	-11	+5	+9	+11	-2	+3	+3	+4
August 1974	22	-5	-8	-10	15	-3	-5	-6
February 1975	-13	+6	+10	+11	-3	+4	+5	+5
May 1975	14	-1	-1	-1	14	-3	-2	-2
February 1976	-11	+4	+8	+10	-3	+3	+4	+5

14/Durability of Styrofoam™ Insulation

Three different thicknesses of STYROFOAM™ samples (25 mm, 50 mm and 75 mm), approximately 0.45 m square, were recovered near the wheel path of the driving lanes of the highway after being buried under the roadway for five years. The recovery procedure involved removing 75 mm of asphaltic concrete pavement and 460 mm of granular base course. Two samples (25 mm and 75 mm) were removed from the northbound driving lane and the remaining one sample (50 mm) was recovered from the southbound lane.

All recovered samples were immediately sealed in polyethylene bags for transporting to the laboratory. Before laboratory testing, dirt on the surface of the samples was carefully removed by washing.

Table 7 summarizes the laboratory results of tests on the three STYROFOAM™ samples removed from the pavement.

Only in the 25 mm thick sample was there an observed loss in measured thermal conductivity in the wet state. As for the 50 mm and 75 mm thick samples, both showed negligible moisture pick-up, and hence no significant change in thermal conductivity after all these years. Furthermore, all three test samples had exhibited no decrease in thickness and no reduction in minimum vertical compressive strength of 240 kPa.

Table 7/ Laboratory Test Results of STYROFOAM™ Samples

Sample Identification	'K' Factor (wet) AsTM C-518 $\frac{W}{m^2 - 0°C}$	'K' Factor (dry) ASTM C-518 $\frac{W}{m^2 - °C}$	Water Content % by Volume	Dry Density FP-3 kg/M³	Vertical Compressive Strength @ 5% Defl. kPa	Vertical Compressive Strength @ 10% Defl. Kpa	Vertical Compressive Modulus kPa
25 mm STYROFOAM HI-35	1.329	1.203	3.95	37.49	291.7*	337.9*	8964*
50 mm STYROFOAM HI-35	1.260	1.203	1.29	40.05	519.2	577.8	12742
75 mm STYROFOAM HI-35	1.243	1.197	0.93	33.00	344.1	344.1	13204

* Irregularity in surfaces were removed.

15/Computer Analysis

The ability to accurately predict the depth of frost penetration beneath highways with or without insulation can be a valuable tool for the designer. A part of this project consisted of testing the accuracy of a computer prediction program developed by Dr. F.S. Wang of Dow Chemical Company of Canada Limited [15].

The program not only provides detailed predictions of frost depths and ground temperatures, but can be used for designing for the worst possible conditions or for determining the optimum designs for new pavement structures using experimental materials.

The model used is described as a two–dimensional finite element program for transient heat flow conduction. The model is capable of handling a multi–layered soil profile, with layers of varying thicknesses and thermal properties.

Computer simulations were run for all of the Val Gagne sections based on 1975–1976 actual weather data. Complete details regarding these simulation runs can be found in reference 15.

15.1/Input Data

The 1975–1976 climatological data required for the simulation was obtained from the Climatological Station at Iroquois Falls. Soils information available from the Soils Report [8] was sufficient to characterize the thermal properties of the embankment and foundation soils. Thermal properties of the soils and insulation layers used in the simulation are listed in Table 8.

Table 8/ Thermal Properties of Embankment Layers

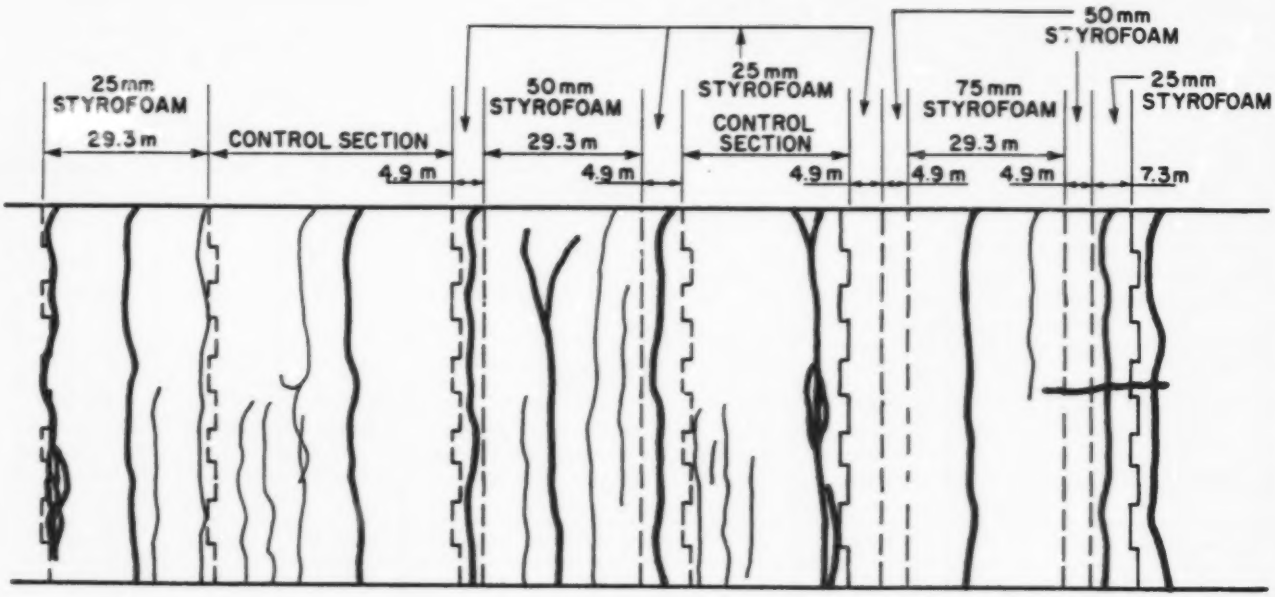
Material Layers		Dry Density kg/m³	Water Content %	Thermal Conductivity $\frac{W^\circ}{m^2\ {}^\circ C}$		Volumetric Heat $\frac{KJ}{m^3\ {}^\circ C}$		Latent Heat of Fusion KJ/m³
				Frozen	Thawed	Frozen	Thawed	
Asphaltic Concrete		2371	0	58.60	58.60	3078.3	3078.3	16543
Gravel Base		2211	6.5	85.17	85.17	2608.9	2917.4	48138
STYROFOAM HI-35		36.8	0	1.1356	1.1356	48.29	48.29	0
Subgrade No. 1	Control Section	1698	22	87.21	65.41	2629.0	4124.6	125116
(Silty Clay)	25 mm	1394	38	96.07	51.78	2682.6	4319.1	177380
1.5 m to 2.4	50 mm	1666	15	59.96	53.15	2554.0	3554.5	83684
	75 mm	1458	31	88.58	52.46	2608.9	4091.0	151346
Subgrade No. 2	Control Section	1089	51	87.90	36.11	2602.2	3755.7	184693
(Silty Clay)	25 mm	1009	61	96.07	34.07	2582.0	4285.5	166958
2.4 m to 7.6 m	50 mm	961	67	98.80	32.71	2629.0	4500.1	215320
	75 mm	977	62	92.66	32.71	2608.9	4426.4	205260

Table 9/ Computer Prediction of Maximum Frost Penetration as Compared with Site Measurements

Section	Predicted 0°C Isotherm depth (m)		
	Thermocouples	Frost Indicators	Computer (daily air)
Control no insulation	3.10	2.59	2.59
25 mm insulation	2.71 (2.18)	1.90 (1.37)	1.93 (1.40)
50 mm insulation	2.08 (1.55)	1.22 (0.69)	1.90 (1.37)
75 mm insulation	1.65 (1.12)	1.02 (0.49)	1.47 (0.94)

Numbers in parenthesis represent measurements taken below the STYROFOAM level.

Figure 19/ Pavement Cracking Pattern After the Five Year Test Period



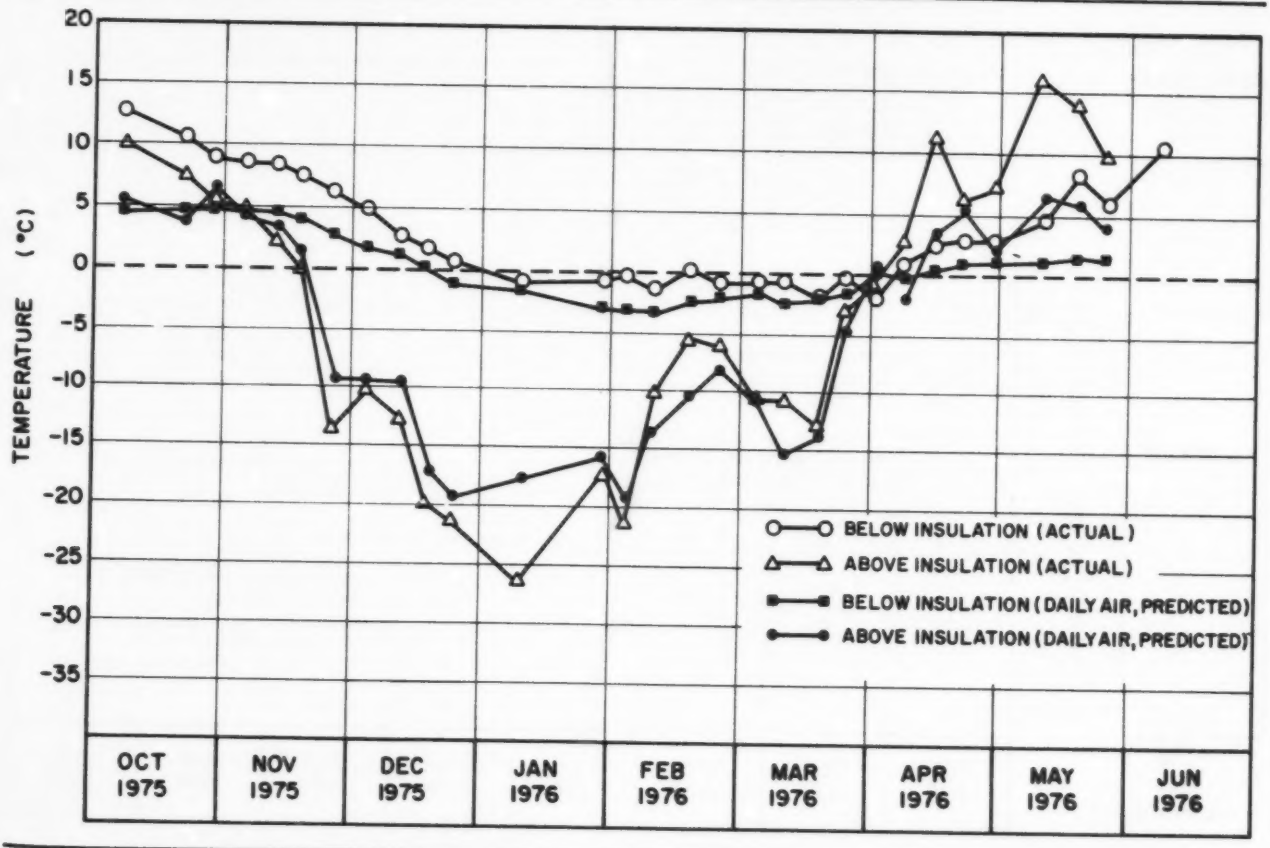
15.2/Temperature Distribution Results

Figure 20 is an example of the comparison between the observed and computed temperatures directly above and below the 75 mm insulating layer. As clearly shown,the prediction model correlates well with the thermocouple results when the actual temperature pattern is used. Variations in the results can be caused by many factors, such as the effect of snow cover, variation of soil types and time–temperature distribution.

15.3/Frost Penetration

The comparison between the predicted and the measured maximum penetration of the 0°C isotherm is shown in Figure 21 for the 25 mm and 75 mm sections, and the results for all sections are given in Table 9. An examination of the data shows that the computer prediction agrees well with the measured penetration in both the non–insulated control and the 25 mm sections. However, the program predicts almost identical frost penetration for both the 25 mm and 50 mm sections. This is not in agreement with measurements from the frost depth indicators which show not only less penetration but a substantial difference in penetration between the 25 mm and 50 mm sections.

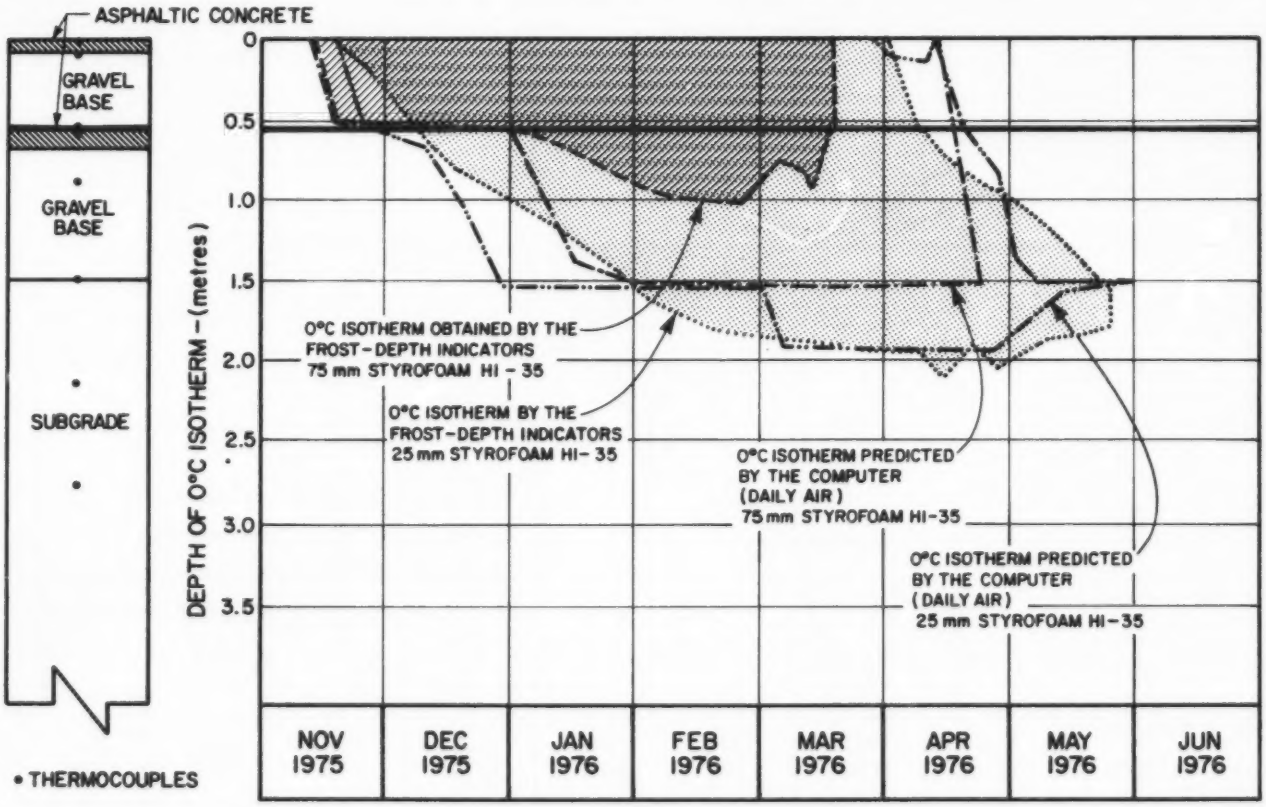
Figure 20/ Observed and Computed Temperatures Directly Above and Below the 75 mm STYROFOAM™ Layer at the Centreline



An example of the predicted and measured frost penetration in the transverse direction is shown in Figure 22. It can be seen that the simulated pattern of frost penetration corresponds quite closely with the measured penetration.

In summary, the computer program now available closely predicts the frost penetration beneath the 25 mm STYROFOAM™ and uninsulated sections. The program over-predicts the frost penetration in the thicker 50 mm to 75 mm STYROFOAM™ sections.

Figure 21/ Maximum Depths of Measured and Predicted Frost Penetration for the 25 mm and 75 mm Sections



16/Design of Styrofoam™ Treatments

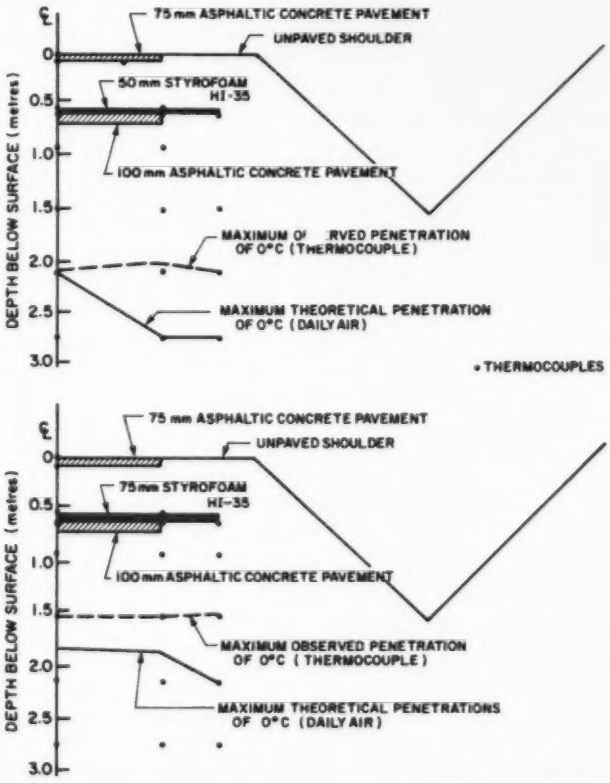
On the basis of the measurement of frost penetration at Val Gagne and other sites with STYROFOAM™ insulation, a diagram of frost penetration versus thickness of STYROFOAM™ insulation for different temperature environments was created. (Refer to the chart in Figure 23.) The frost penetration with no insulation was calculated from the prediction formula:

$$P = -0.328 + 0.0578 \sqrt{F}$$

and represents a five–year average value [7]. This chart allows the designer to determine the insulation thickness needed to "control" the penetration of frost to any desired depth, such as needed to control frost heaving.

For example; in an environment of 2000 degree–days Celsius, if frost may penetrate 1.5 m without excessive heave, 40 mm is the standard thickness of insulation needed for the treatment.

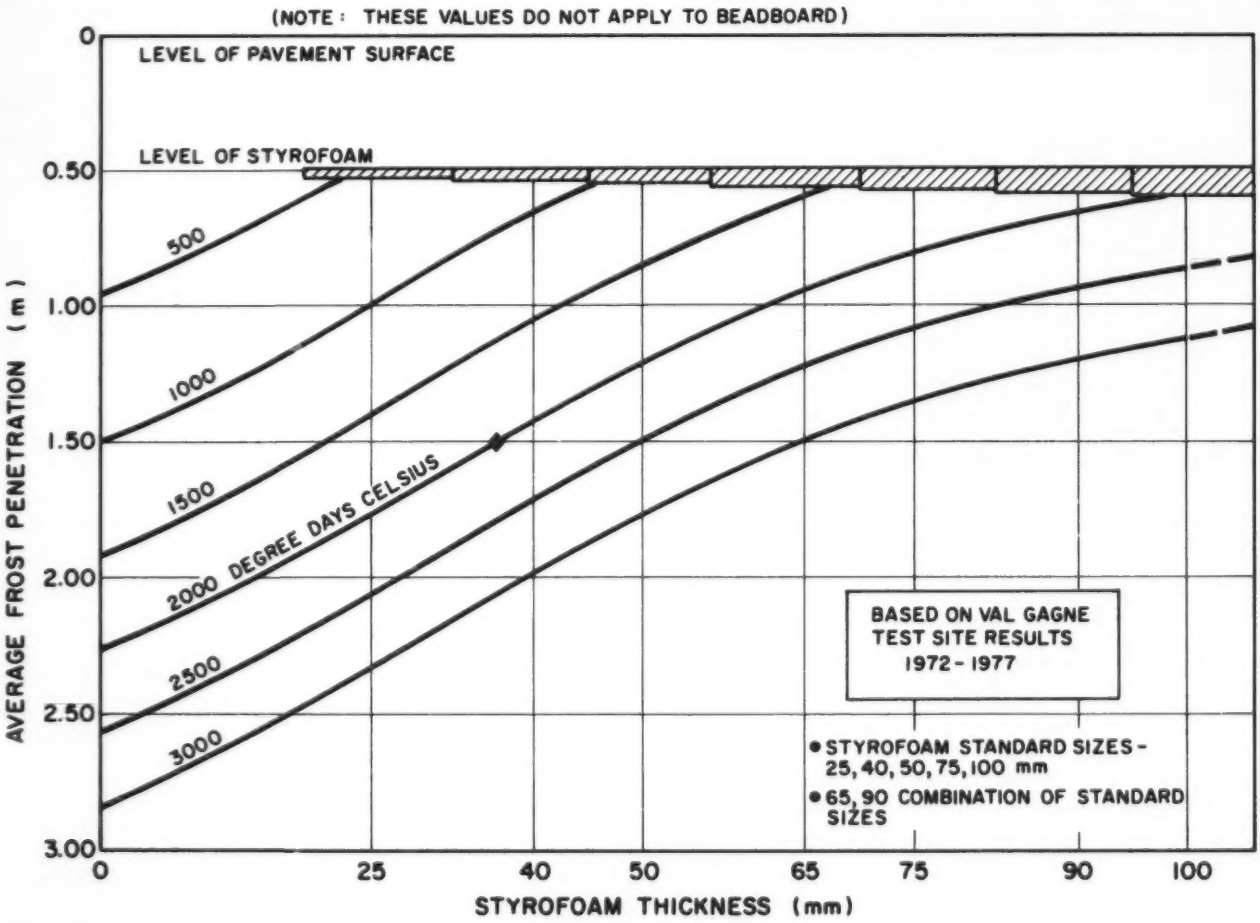
Figure 22/ Comparison of Measured and Predicted Maximum Frost Penetration in the Transverse Direction



17/Concluding Remarks

- Experience has shown that frost depth probes are more reliable indicators of the location of the frost front than instantaneous thermocouple readings. Thermocouple readings taken on a continuous automatic basis will give reliable frost penetration results.
- Longer lengths of transition tapers do result in a reduction in the abruptness of the bump at the end of the insulation caused by differential heave. However, in this experiment, the differential heave was not very large and no recommendation is made to increase standard taper length.

Figure 23/ Average Penetration of Frost Beneath STYROFOAM® in Paved Highways



18/Recommendations

- Frost measurements made transversely indicate that reducing the standard width of the insulation beyond the pavement edge from 1.8 m to 1.2 m would not substantially alter the frost penetration profile.
- At this site, a depth of cover of 460 mm of gravel base adequately protects the insulation from the effects of construction equipment and traffic, so that there was no detectable change in the final insulation thickness. As well, over the five years of tests, only the 25 mm thick insulation showed any detectable change in thermal insulating value.
- The insulation not only retards the escape of ground heat to the air during winter, it retards the replenishment of ground heat storage during the summer months. However, the observations at this site are not adequate to show effects of reduced heat storage on frost penetration.
- The computer simulation program accurately predicts the frost penetration of uninsulated pavements and thin (25 mm) insulated sections. The computer predicts deeper frost penetration than actual for the thicker (50 mm, 75 mm) insulated sections. The measurements at the site can be used to check future modifications to the computer program made to more accurately predict penetration for thicker insulation.

[1] The chart for frost penetration under different thicknesses of STYROFOAM® insulation may be used to select insulation for controlling frost heave.

[2] Further refinements which are needed to the computer simulation program for the thicker lifts of insulations should be examined.

[3] The standard width of insulation may be reduced by 0.60 m on either side of the cross sections.

[4] Further tests should be carried out on recovered samples of the 25 mm thick insulation.

19/Definitions

Degree–Days: The degree–days for one day equals the difference between the average daily air temperature and 0°C. The degree days are minus when the average daily temperature is below 0°C (freezing degree–days) and plus when above 0°C (thawing degree–days).

Freezing Index: The number of degree–days (above and below 0°C) between the highest point in the autumn and the lowest point the next spring on the cumulative degree–day time curve for one freezing season.

Mean Freezing Index: The freezing index determined on the basis of mean temperatures. The period of record over which temperatures are averaged is usually a minimum of 10 years (preferably 30) and should be the latest available.

Design Freezing Index: The average air freezing index of the three coldest winters in the latest 30 years of record. If 30 years of record are not available, the air freezing index for the coldest winter in the latest 10–year period may be used.

Average Daily Temperature: The average of the maximum and minimum temperatures for one day or the average of several temperature readings taken at equal time intervals during one day.

Frost Heave: The raising of a surface due to formation of ice in the underlying soil.

Plasticity Index: The difference between the liquid limit and the plastic limit PI is an indication of the change that can take place in the moisture content of the soil before the soil goes from a semi–solid to a liquid condition.

Liquid Limit: The water content at which a soil passes from the plastic to the liquid state.

Plastic Limit: The moisture content at which a soil changes from a semi–solid to a plastic state.

Frost–Susceptible Soil: Soil in which significant detrimental ice segregation will occur when the requisite moisture and freezing conditions are present.

Non Frost–Susceptible Soil: Noncohesive materials such as crushed rock, gravel, sand, slag, and cinders in which significant detrimental ice segregation does not occur under normal freezing conditions.

Stevenson Screen: A small box used to protect meterological instruments in the field.

Bench Mark: A mark on a permanent object indicating elevation and serving as a reference for future elevations. The bench marks are not affected by frost action.

Thermohydrograph: A mechanical device used in taking continuous measurments of temperature and humidity.

Thermocouple: A thermoelectric couple used to measure temperature differences.

Thermal Conductivity ("K" Factor): Time rate of transfer of heat by conduction through unit thickness, across unit area for unit difference of temperature.

0° Isotherm: The depth in the pavement structure at which the soils change from a frozen to an unfrozen state. This would represent the maximum frost penetration at the time the readings were taken.

Volumetric Heat Capacity: The quantity of heat required to change the temperature of a unit volume by one degree Celsius.

Latent Heat of Fusion: The quantity of heat required to melt the ice (or freeze the water) in a unit volume of soil without a change in temperature.

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